ABSTRACT

Title of Document: A HAPTIC SYSTEM FOR DEPICTING MATHEMATICAL GRAPHICS FOR STUDENTS WITH VISUAL IMPAIRMENTS

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When teaching students with visual impairments educators generally rely on tactile tools to depict visual mathematical topics. Tactile media, such as embossed paper and simple manipulable materials, are typically used to convey graphical information. Although these tools are easy to use and relatively inexpensive, they are solely tactile and are not modifiable. Dynamic and interactive technologies such as pin matrices and haptic pens are also commercially available, but tend to be more expensive and less intuitive. This study aims to bridge the gap between easy-to-use tactile tools and dynamic, interactive technologies in order to facilitate the haptic learning of mathematical concepts. We developed an haptic assistive device using a Tanvas electrostatic touchscreen that provides the user with multimodal (haptic, auditory, and visual) output. Three methodological steps comprise this research: 1) a systematic literature review of the state of the art in the design and testing of tactile and haptic assistive devices, 2) a user-centered system design, and 3) testing of the system's effectiveness via a usability study. The electrostatic touchscreen exhibits promise as an assistive device for displaying visual mathematical elements via the haptic modality.

Keywords: Haptic, Visual impairment, Blind, Assistive technology, User-centered design, Electrostatic, Mathematics, Touchscreen, Education, Graphs.

A HAPTIC SYSTEM FOR DEPICTING MATHEMATICAL GRAPHICS FOR STUDENTS WITH VISUAL IMPAIRMENTS

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Introduction

Across the world, there are approximately 285 million people who have visual impairments (World Health Organization, 2012). There are 694,000 school-aged individuals with visual impairments in the United States alone (Erickson, Lee, & von Schrader, 2014). Of the students with visual impairments who are eligible to receive adapted educational materials, 83% receive their education in mainstream classrooms, which are often not equipped with adequate educational tools for the visually impaired (American Printing House for the Blind, 2015). These students tend to fall behind in STEM coursework (Beck-Winchatz & Riccobono, 2008). This trend can be attributed to the highly visual nature of graphical mathematical concepts, which often require spatial reasoning skills (Nam, Li, Yamaguchi, & Smith-Jackson, 2012).

Tactile graphics are often used to present mathematical concepts to students with visual impairments, however, the tactile modality cannot portray the same density of information as can the visual modality (Smith & Smothers, 2012). Prior research in the fields of tactile perception theory and cognitive psychology has contributed to a broader understanding of how people with visual impairments interact with sensory inputs. Specifically, research has supported haptic technology, which incorporates kinesthetic feedback into tactile media, as a viable tool for communication with people with visual impairments (Klatzky & Lederman, 2003). Congenitally blind individuals have a fully developed ability to understand spatial information (e.g. shape, distance) from tactile input (Tinti et al, 2006), as well as the ability to distinguish between rapid tactile stimulations better than their sighted or adventitiously blind counterparts (Röder, Rösler, & Spence, 2004), implying that individuals with visual impairments have the capacity to understand information presented via a haptic touchscreen device.

Objectives

This research aims to develop an electrostatic touchscreen system for displaying visual mathematical elements to students with visual impairments via the haptic modality, and to test the usability of such a device. The specific aims are:

1. To lay the groundwork for devising, improving, and implementing new technologies to meet the needs of individuals with visual impairments. A systematic literature review was conducted to provide insightful information for future research about effective design strategies of assistive technology for individuals with visual impairments.
2. To integrate an electrostatic touchscreen display and develop software that will translate graphical mathematical information to the haptic modality. The device consists of a Microsoft Surface Pro 2 tablet and a Tanvas electrostatic touchscreen overlay, which generates the perception of texture on a user's finger.
3. To investigate the effectiveness and the efficiency of the device in portraying graph elements haptically. Participants were subject to a protocol composed of six tasks testing the user's ability to interact with the device. The accuracy and efficiency of task completion were analyzed to determine the device's potential as an assistive device for future classroom use.

Delineation

The chapters of this thesis were structured in the form of articles, as suggested by Thomas and Nelson (2002). This thesis is split into five main bodies: an introduction, three chapters, and a conclusion. Chapter I presents previous research pertaining to the design and usability of assistive technologies. Chapter II presents the user-centered design of the device, with multiple phases of expert feedback and software design, which aims to optimize the device for individuals with visual impairments. Chapter III presents results from usability testing to assess the ability of the electrostatic touchscreen to depict mathematical concepts to individuals with visual impairment.

Chapter I: A Review of Principles in Design and Usability Testing of Tactile Technology for Individuals with Visual Impairments[1]

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Abstract

To lay the groundwork for devising, improving, and implementing new technologies to meet the needs of individuals with visual impairments, a systematic literature review was conducted to: a) describe hardware platforms used in assistive devices, b) identify their various applications, and c) summarize practices in user testing conducted with these devices. A search in relevant EBSCO databases for articles published between 1980 and 2014 with terminology related to visual impairment, technology, and tactile sensory adaptation yielded 62 articles that met the inclusion criteria for final review. It was found that while earlier hardware development focused on pin matrices, the emphasis then shifted toward force feedback haptics and accessible touch screens. The inclusion of interactive and multimodal features has become increasingly prevalent. The quantity and consistency of research on navigation, education, and computer accessibility suggest that these are pertinent areas of need for the visually impaired community. Methodologies for usability testing ranged from case studies to larger cross-sectional studies. Many studies used blindfolded sighted users to draw conclusions about design principles and usability. Altogether, the findings presented in this review provide insight on effective design strategies and user testing methodologies for future research on assistive technology for individuals with visual impairments.

Keywords: Education, Electronic aids to daily living, Emerging trends, Usability, Visual impairment, Computer access.

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Introduction

The quality and quantity of assistive technologies available for individuals with visual impairments have grown substantially as computers have become more available and increasingly complex hardware platforms have entered the market. The concept of sensory substitution for individuals with visual impairments was initially discussed by Bach-y-Rita et al. in a seminal study showing that the adult brain has sufficient neuroplasticity to substitute tactile stimuli for visual information (1969). The first mainstream sensory substitution devices, such as the Optacon and Tactile Vision Substitution System, were based on an array of pins that could be raised and lowered to create refreshable images (Bach-Y-Rita & Hughes, 1985). When text-to-speech software improved, audio became another mode of conveying information. As technology has developed in other fields, including human-computer interaction, devices that are able to provide increasingly precise and responsive tactile feedback, often called haptics, have also become available (Kahol, Tripathi, & Panchanathan, 2005). More recently, haptic feedback, virtual environments, and multimodal adaptations have been on the rise, with focus on making mainstream technology such as touch screens accessible for those with visual impairments (Kane, 2011; Yao & Leung, 2012). As new devices are designed and tested, it is important to evaluate these experiences to determine what platforms have been used most successfully, what design principles have been found to be the most effective, and what strategies can be used to include individuals with visual impairments in the process.

Significant progress has been made in terms of product reliability and effectiveness of assistive devices. Research on haptic perception and multimodality has significantly contributed to a broader understanding of how non-visual sensory information is perceived (Klatzky & Lederman, 2003). Haptic perception integrates signals from the skin receptors and proprioceptors to allow for object and pattern identification and recognition (Rincon-Gonzalez, Naufel, Santos, & Helms Tillery, 2012). Those who are blind rely particularly on haptic perception to process external stimuli and spatial information. Research has shown that individuals with congenital blindness experience enhanced vibrotactile perception (Wan, Wood, Reutens, & Wilson, 2010) and spatial resolution, and that individuals who are blind are less likely to experience an age-related decline in tactile acuity than their sighted counterparts (Legge, 2008). This is useful in conveying spatial information, as research has also shown that even individuals with congenital blindness have a fully-developed ability to understand spatial information from tactile input (Tinti, Adenzato, Tamietto, & Cornoldi, 2006; Guidice, Betty, & Loomis, 2011). In addition to having enhanced sensory perception, research by Withagen et al. suggests that children who are blind tend to have better short-term memory and verbal working memory, which play a role in auditory and tactile processing, than their sighted counterparts (2013). Therefore, assistive devices commonly provide multiple modes of feedback, such as touch and sound, to convey information (Yu, Kangas, & Brewster, 2003). This is supported by more general research on multimodality, which has shown that it is often most effective to communicate information through more than one sensory channel (Turk, 2014).

The incorporation of a user testing process, in which individuals from the intended user population test the device and give feedback about its ability to meet their needs, is an essential element of the design process. Over time, the principles of iterative user-centered design have been increasingly emphasized as best practices in the field of user testing, and are used to ensure the accessibility of software and devices (Petrie & Benev, 2009). Iterative user-centered design requires that user feedback be included throughout the entirety of the design process, from identifying user needs to prototyping and final testing. The goal of this approach is to design devices that more closely fit the needs of the intended user population (Nielsen & Landauer, 1993). While user testing can be a challenge in device development for smaller target audiences, such as individuals with visual impairments, many of the studies included in this review successfully incorporate extensive user testing into the device design process (Ashcroft, 1983; Tzovaras, Nikolakis, Fergais, Malasiotis, & Stavrakis, 2004; Ando, Tsukahara, Seki, & Fujie, 2012).

This systematic literature review has three distinct aims: 1) to determine how the technologies available have historically contributed to research on assistive devices, in order to depict a landscape of hardware platforms used in the development of assistive devices; 2) to categorize and discuss the main accessibility issues addressed by researchers while developing assistive devices; and 3) to systematically examine the methodologies previously adopted to test the usability of assistive devices.

Methods

Data sources

A systematic review was conducted to identify the available findings and evidence on assistive technology for individuals with visual impairments in a methodical and replicable manner (Torgerson, 2003). Articles were identified within several databases in the EBSCO suite covering academic literature on technology, disability, and education. The databases included were Academic Search Premiere, the Psychology and Behavioral

Sciences Collection, Education Research Complete, Business Source Complete, Computers & Applied Sciences Complete, and the Education Resources Information Center.

A combination of search terms was used to locate articles published between 1980 and 2014 that mentioned terms related to visual impairment (blind OR "visually impaired" OR "visual impairment*"), technology (device OR technology OR interface), and sensory adaptation (haptic OR tactile OR multimodal) within the title or abstract. Results were filtered to only include articles classified as Academic Journals, Reports, Trade Publications, or Conference Proceedings. Duplicate citations were removed in cases where the same article was indexed in multiple databases.

Inclusion/Exclusion Criteria

From the initial set of articles that matched these search terms, relevant articles were identified from an initial screening of the title/abstract alone followed by an in-depth review of the full text of the remaining articles.

Articles included in the final review met all of the following criteria:

1. Article addresses the development of a personal, electronic, assistive device with a tactile component.
2. Technology is developed specifically for users who have some form of visual impairment.
3. Article describes the original development or testing of a specific device.
4. Article includes the results of testing by at least one user who is blind or visually impaired.

Articles were excluded from the review if they met any of the following criteria:

1. Article is a review of studies on multiple devices and does not include a sufficiently detailed description of a single device.
2. Article describes a system that has no electronic or computational component (e.g. papers describing swell paper or tactile models alone) or no tactile component (e.g. devices with only an auditory output).
3. Article does not mention testing the device with users.
4. Article mentions testing the device with sighted users, but does not indicate testing with at least one user who is blind or visually impaired.
5. Article describes the design of a device implemented in a public space (e.g. crosswalks or signs) and not the development of a personal device.
6. Article describes a device designed solely to collect data in a research setting, and not to act as an assistive device to the user.

In order to gain a broad view of the types of technology available, this review was not limited to devices used for a specific type of application (e.g. reading, navigation, or learning). However, it was limited to personal, electronic devices because the issues faced in designing public assistive technologies and accessible public spaces are distinct from those faced in designing personal devices. Devices that did not include at least some tactile component were also excluded. To specifically identify research on devices that have been used by the visually impaired community or could be used in the future, the studies reviewed were limited to those that had conducted at least some level of user testing. It was required that the devices were tested by at least one person with a visual impairment, as opposed to only sighted users, because it is well documented that there are significant differences in how people with and without visual impairments perceive information and interact with devices (Bach-Y-Rita & Kercel, 2003).

To focus on relatively current research, the search was limited to articles published after 1980 because the quantity of research published on assistive devices for individuals with visual impairments substantially increased in the early 1980s (Smith & Kelly, 2014). General review articles that did not include specific information about individual devices, but may have provided a broader or more complete analysis of device development, were excluded.

The initial search yielded 300 results, excluding duplicate listings between databases. Of these articles, 62 were determined to be relevant after a first pass title/abstract review followed by a second pass reading of the full text of remaining articles (see Table 1.1). All decisions were cross-checked by a minimum of two reviewers to ensure consistency in the application of the inclusion/exclusion criteria. Most articles excluded in the first pass were either not about the topic of visual impairment or did not describe a specific personal, assistive device. Most articles excluded during the full text review were excluded because the study did not mention usability testing with at least one user who is blind or visually impaired.

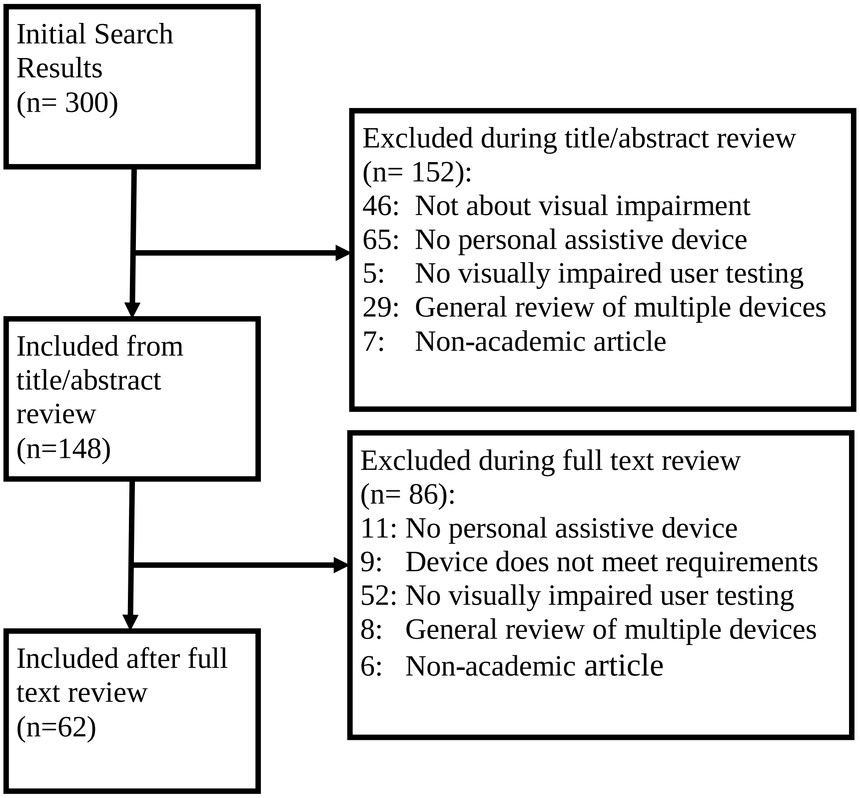

Table 1.1: Flow of articles through selection process.

Data Extraction

From each included article the following information was collected in a standardized matrix: title, author, year of publication, number of users who tested the device (stratified by level of visual impairment, age, and gender of participants where possible), hardware platform mode of user interaction (e.g. tactile and/or auditory), significant results of device development and/or testing, and intended application of the technology (e.g. navigation, education, etc.). The information collected in this matrix was then used to synthesize the data into summary tables for each specific aim, indicating patterns in user testing, choice of hardware platform, and application area among devices.

Results

Hardware Platforms

The availability of increasingly complex, responsive, and adaptable hardware platforms has driven improvements in assistive technologies for individuals with visual impairments. The first specific aim of this review is to identify which hardware platforms were the most widely used and served as a basis for the development of effective assistive devices. In order to gain a broad view of the progression of device development, papers were first categorized by the hardware platform they used for device development (see Table 1.2). Most systems were based on one of three basic hardware categories:

1. Pin matrices, which are tactile displays built from an array of small pins that can be individually raised or lowered to create an image, similar to braille. Pin matrices permit users more than one point of contact and provide representations that most resemble real world counterparts. However, pin matrices are limited in resolution due to the spacing of the pins; likewise, their high cost make them relatively unavailable to most blind persons (O'Modhrain, Giudice, Gardner, & Legge, 2015).
2. Force feedback systems, which generate a force on the user's finger or hand as it moves to communicate spatial information. Many of these systems are restricted to a single point of contact and provide more abstract tactile information that the user must learn to interpret. Benefits include rapid rendering, three dimensional renditions, and presentation of both static and dynamic effects (O'Modhrain et al., 2015).
3. Tablets and touch screens, which combine vibration and/or auditory feedback with standard visual displays. Currently, many touch screens are limited by their

resolution, single point of contact, and the inability to provide stimulus when the user’s finger is not in motion on the screen. They are promising in that they are quickly refreshable and less expensive than pin matrices (O'Modhrain et al., 2015).

People with visual impairments have used all three types of devices successfully, and each has its advantages in communicating information quickly and efficiently. The hardware components of the devices reviewed varied widely in complexity. While some devices included complex tactile systems, others were based almost exclusively on interaction with a standard interface such as a computer. Recently, several devices have been developed using vibration and auditory feedback from standard touch screens and tablet devices to make graphical material accessible (Giudice, Palani, Brenner, & Kramer, 2012; Poppinga, Magnusson, Pielot, & Rasmuss-Grohn, 2011). New technology has entered the market that allows for the development of touch screens that provide tactile feedback to the user through electrostatic interaction. This may allow future development of assistive technologies for applications in which the use of a tactile touch screen is extremely practical (Kim, Israr & Poupyrev, 2013).

Many of the reviewed papers discussed custom-built devices, most still in the prototyping phase, designed for a fairly specific application or population of users. These devices included tactile displays, computer interfaces, force feedback canes, tactile stimulators for various parts of the body, and virtual reality systems (Velasquez, Bazan, Varona, Delgado-Mata, & Gutierrez, 2012; Zelek, Bromley, Asmar, & Thompson, 2003; Tzovaras et al., 2004). A few commercially available devices, however, have been studied extensively for a broad variety of accessibility needs. One of the first pin-matrix devices was the Optacon, a pen-shaped device with a camera on one end that translated images to a small pin matrix on the other. This was used in a variety of ways, from reading text to viewing images, and was the precursor to even larger and more complex pin matrix displays (Bach-Y-Rita & Hughes, 1985). The most widely studied force-feedback device in this review is the Phantom, a device that applies varying forces to the user's finger as they move it around to simulate contact with objects in a virtual environment (Sjostrom & Rassmus-Grohn, 1999). A more recent commercially available technology is the Talking Tactile Tablet, a tablet that can have swell paper images attached on its surface and plays programmed auditory feedback when the user touches certain areas of the picture. This has been applied especially well in educational and assessment environments (Hansen, Shute, & Landau, 2010; Landau, Russel, & Erin, 2006; Rovira & Gapenne, 2009).

The devices that have successfully been made commercially available have several characteristics in common: they are simple and flexible enough to be adapted for a variety of applications, they communicate information to the user in an interactive way, and they can be combined with auditory feedback or other types of input to create a multimodal environment for the user. While the optimal design parameters for each device vary widely based on the application it is intended for, as well as the needs of the individual user, many of the articles reviewed emphasized the advantages of these overarching design principles.

Device Type	**Device Description**	**References**
Pin Matrix	Optacon	Bach-Y-Rita & Hughes, 1985; Miletic, 1994; Miletic, Hughes, & Bach-Y-Rita, 1988
	Braille Cells	Rastogi & Pawluk, 2013; Rastogi, Pawluk, & Ketchum, 2013; Al-Qudah et al., 2014
	Pin Board	Guha & Anand, 1992; Ebina et al., 1999; Kurze, 1999; Kawai & Tomita, 2000; Watanabe & Kobayashi, 2002
Force Feedback	Haptic Glove	Zelek et al., 2003; Tzovaras et al., 2004; Kahol & Panchanathan, 2008; Bargerhuff et al., 2010; Quek & Oliveira, 2013
	Phantom	Sjostrom & Rassmus-Grohn, 1999; Brewster, 2002; Sjostrom et al., 2003; Bernareggi, Mussio, & Parasiliti Provenza, 2009; Magnusson & Rassmus-Grohn, 2005; Saarinen et al., 2006; Jones et al., 2006; Moustakas et al., 2007; Tuominen et al., 2008; Lahav et al., 2011; Plimmer et al., 2011; Chit & Yap, 2012; Kaklanis, Votis, & Tzovaras, 2013; Lahav, Schloerb, & Srinivasan, 2013; Paneels et al., 2013; Simmonett & Ryall, 2013
	Body Site Specific (other than hands)	Simpson et al., 2005; Marston et al., 2007; Williams et al., 2011; Velazquez et al., 2012
	Handheld-Cane/Rod	Hill & Black, 2003; Zelek, 2005; Ceipidor et al., 2009; Tzovaras et al., 2009; Ando et al., 2012; Jones et al., 2014
	Force Feedback Mouse	Edwards et al., 2005; Jacko et al., 2005; Yu et al., 2006; Thebpanya, 2010
	Game Controller	Raisamo et al., 2007; Petridou et al., 2011; Nam et al. 2012
	Other	Lahav & Mioduser, 2004; Ghiani, Leporini & Paterno, 2009
Tablet/Touch Screen	Tactile Tablet	Landau et al., 2003; Landau, Russel, & Erin, 2006; Rovira & Gapenne, 2009; Hansen, Shute, & Landau, 2010; Wang, Li & Li, 2012
	Touch Screen	Kane, 2011; Gorlewicz et al., 2014
Other	Computer	Ashcroft, 1983; Locke & Mirenda, 1988; Wake, Wake & Takahashi, 1999; Armstrong & Murray, 2010

Table 1.2: Classification of hardware platforms.

Applications of Assistive Devices

The second specific aim of this review is to identify the intended applications for these assistive devices in order to determine which specific needs of the visually impaired community are being addressed by current research. After categorizing articles based on application (see Table 1.3), it was found that the most common applications of assistive technologies for individuals with visual impairments are navigation, education, and computer accessibility. These have been consistently identified as areas where assistive technology can benefit individuals with visual impairments. However, there is still much room for improvement in the technology available to address each of these challenges, and therefore they should remain important themes for future research.

Twenty-six studies, over a third of the reviewed articles, intended to teach or improve learning for students who are visually impaired. Of these, 12 covered STEM topics, from mathematical graphs (Gorlewicz, Burgner, Withrow, & Webster, 2014) to model-based astronomy and geology (Saarinen et al., 2006) to information technology (Armstrong & Murray, 2010). As the overall need for STEM education has increased, there is an increasing emphasis on research in this field, as all 12 of these studies were published after 2000. Another nine studies focused on more general educational needs such as data visualization (Paneels, Ritsos, Rodgers, & Roberts, 2013) and spatial cognition (Miletic, 1994). Three focused on teaching writing and drawing, while another three focused on occupational skills such as identifying common objects (Chit & Yap, 2012) and using ATM machines (Wake, Wake, & Takahashi, 1999).

Several educational studies successfully created virtual reality environments for object exploration, emphasizing the benefits of providing guided exploration (Saarinen et al., 2006; Tuominen et al., 2008), reference points (Saarinen et al., 2006), and clear boundaries (Bernareggi, Mussio, & Parasiliti Provenza, 2009; Jones et al., 2014) to orient students in the virtual reality environment. Many studies demonstrated the benefits of providing multimodal output (Plimmer, Reid, Blagojevic, Crossan, & Brewster, 2011; Nam, Li, Yamaguchi, & Smith-Jackson, 2012; Gorlewicz et al., 2014), particularly using synthesized speech to provide additional context or feedback to the student (Sjostrom, Danielsson, Magnusson, & Rassmus-Grohn, 2003; Tuominen, Kangassalo, Hietala, Raisamo, & Peltola, 2008; Hansen, Shute, & Landau, 2010). The effectiveness of haptic, multimodal technology for learning has been confirmed through educational and cognitive research (Sankey, Birch & Gardiner, 2010).

The next largest application was navigational aid, addressed by 19 of the studies examined. As the technology available for assistive devices has improved, it has greatly expanded the possible platforms for navigational aids, and all 19 of the studies in this review addressing navigation were published after 2000. The prevalence of research in this area reiterates the importance of daily navigation for those who are visually impaired. Ten of these studies investigated navigation through physical environments and obstacles by providing information such as accessible maps (Wang, Li, & Li, 2012; Moustakas, Nikolakis, Kostopoulos, Tzovaras, & Strintzis, 2007), real-time directions based on the user's location (Marston, Loomis, Klatzky, & Golledge, 2007), and feedback about the surrounding area (Zelek et al., 2003). The majority of these articles showed that haptic feedback is particularly useful for aiding in obstacle avoidance (Hill & Black, 2003; Zelek et al., 2003; Simpson et al., 2005; Ghiani, Leporini, & Paterno, 2009).

The remaining eight navigation studies created and explored virtual reality representations of physical environments. Research has shown that users can successfully transfer spatial information from virtual environments to physical environments, and that users trained in in virtual environments can perform comparably in navigation tasks to those trained in physical environments (Merabet, Connors, Halko, & Sanchez, 2012). Many virtual reality devices simulate the feedback provided by a cane, as the cane is a familiar explorational tool for many individuals with visual impairments (Tzovaras et al., 2004; Magnusson & Rassmus-Grohn, 2005; Tzovaras, Moustakas, Nikolakis, & Strintzis, 2009; Ando et al., 2012). Studies suggested that there was significant variability in users' exploration strategies (Lahav & Mioduser, 2004; Tzovaras et al., 2009; Lahav, Schloerb, & Srinivasan, 2013), thus emphasizing the need for navigational environments to be adaptable to these different strategies.

Computer accessibility has also been a growing field for device development. Computer accessibility was the focus of 10 of the reviewed articles, eight of which were published after 2000. Three studies used computer games to test their devices, reflecting a growing trend of gamification in research (Deterding, O'Hara, Sicart, Dixon, & Nacke, 2011). Seven studies focused on computer navigation such as menu selection for Graphical User Interfaces (Edwards et al., 2005; Jacko et al., 2005) and web navigation, representation, and display (Yu, Kuber, Murphy, & McAllister, 2006). Research shows that by adding vibrotactile and/or auditory feedback, standard touchscreens can be successfully adapted for use by individuals with visual impairments (Kane, 2011; Gorlewicz et al., 2014). The need for research focusing on touch screen and computer accessibility will continue to increase as a result of computers becoming more commonplace in everyday use and central to society.

The need to address challenges in education, navigation, and computer accessibility remains relevant today, and recent research continues to focus on all of these problems. As accessibility research moves forward, it must address the needs of device users as reflected by these past research trends, while adapting to new needs that arise as technology continues to change.

Application Field	**Application Description**	**References**
Education	STEM Learning	Landau et al., 2003; Sjostrom et al., 2003; Jones et al., 2006; Saarinen et al.,2006; Tuominen et al., 2008; Rovira & Gapenne, 2009; Armstrong & Murray, 2010; Hansen, Shute, & Landau, 2010; Nam et al. 2012; Quek & Oliveira, 2013; Jones et al., 2014; Gorlewicz et al., 2014
	Writing/Drawing	Watanabe & Kobayashi, 2002; Bernareggi, Mussio, & Parasiliti Provenza, 2009; Plimmer et al., 2011
	Occupational Skills	Wake, Wake & Takahashi, 1999; Chit & Yap, 2012
	General	Ashcroft, 1983; Bach-Y-Rita & Hughes, 1985; Locke & Mirenda, 1988; Guha & Anand, 1992; Miletic, 1994; Miletic, Hughes, & Bach-Y-Rita, 1988; Landau, Russel, & Erin, 2006; Petridou et al., 2011; Paneels et al., 2013
Navigation	Physical Environment	Hill & Black, 2003; Zelek et al., 2003; Simpson et al., 2005; Zelek, 2005; Marston et al., 2007; Ceipidor et al., 2009; Ghiani, Leporini & Paterno, 2009; Ando et al., 2012; Wang, Li & Li, 2012; Simmonett & Ryall, 2013
	Virtual Reality	Lahav & Mioduser, 2004; Tzovaras et al., 2004; Magnusson & Rassmus-Grohn, 2005; Moustakas et al., 2007; Tzovaras et al., 2009; Thebpanya, 2010; Lahav et al., 2011; Kaklanis, Votis, & Tzovaras, 2013; Lahav, Schloerb, & Srinivasan, 2013
Computer Accessibility	General Browsing and Navigation	Ebina et al., 1999; Brewster, 2002; Edwards et al., 2005; Jacko et al., 2005; Yu et al., 2006; Kane, 2011; Al-Qudah et al., 2014
	Games	Sjostrom & Rassmus-Grohn, 1999; Raisamo et al., 2007; Bargerhuff et al., 2010
No Specified Application		Kurze, 1999; Kawai &Tomita, 2000; Kahol & Panchanathan, 2008; Williams et al., 2011; Velazquez et al., 2012; Rastogi & Pawluk, 2013; Rastogi, Pawluk, & Ketchum, 2013

Table 1.3: Classification of device applications.

Usability Testing

The final specific aim of this review is to comprehensively analyze usability testing, which offers valuable data in terms of examining past efforts and structuring future studies.

Ideally, studies are able to include a representative group from the population intended to use the device. The fact that 52 articles were excluded in the full text review simply due to lack of user testing by participants with visual impairments indicates that a significant portion of current research is unable to do this. This is partially due to the difficulty that many researchers experience recruiting visually impaired users to validate technology. In the studies including usability testing by blind and visually impaired users, most of the participants were recruited either through word of mouth, from personal connections, or by contacting regional organizations for blind and visually impaired persons. It is essential that usability testing by users with visual impairments is made a priority, as no device can be effectively validated if it is not tested by individuals in the target user audience.

The number of users required for a study can vary widely, whether the intent is to test usability or statistical significance. It is generally accepted that a sample of five to ten users is sufficient for usability testing, and it is estimated that five users are able to find an average of 85% of usability issues (Nielsen & Landauer, 1993; Faulkner, 2003). Alternatively, in studies that require statistically significant results in addition to usability feedback, the number of users required to achieve significant results varies between 11 and upwards of 2,000 users, based on a number of different variables (Cohen, 1992). These larger sample sizes can be difficult to recruit due to the relatively small proportion of people with visual impairments in the general population. However, data from 20 users may be sufficient for significance in many situations (Nielsen, 2006). Table 1.4 shows the distribution of the number of participants with visual impairments included in each study. In studies that included more than one experiment, the experiment that included the largest number of users with visual impairments was counted.

Number of Users with Visual Impairments	**Number of Studies**
1-4	11
5-10	21
11-20	14
> 20	11
Not Specified	4

Table 1.4: Number of users with visual impairments included in study.

In addition to testing with users with visual impairments, 19 of the 62 studies also included testing with sighted users, often blindfolded so that performance could be measured without interference from visual stimuli. Some of these studies purposefully included sighted users as test subjects because the device was intended for use by both visually impaired and sighted populations (Watanabe & Kobayashi, 2002; Kahol & Panchanathan, 2008). Other studies included sighted users as a pilot group to formalize the protocol and identify preliminary usability issues before recruiting users with visual impairments (Wake, Wake, & Takahashi, 1999; Brewster, 2002). Finally, some studies included sighted users as a control group for comparison to the performance of users with visual impairments (Edwards et al., 2005; Quek & Oliveira, 2013). Each of these techniques was used effectively in several of the studies reviewed. However, some other studies mentioned conducting testing with sighted users, but did not specify how this added to the data collected or improved the protocol for the study. Sighted users are not an effective substitute for blind users, as blind and sighted users perceive sensory input differently (Bach-Y-Rita & Kercel, 2003). Therefore, it is only necessary to include sighted users in the protocol if they serve a specific purpose, such as a pilot group or a control group.

Discussion

This systematic literature review aimed to determine which hardware platforms are often used for assistive technologies, to identify prevalent applications of assistive platforms, and to investigate the nature of user studies conducted with assistive technologies for blind individuals. The devices included in this review were limited to those listed in the EBSCO databases and tested with at least one visually impaired user. Of the 300 articles originally identified, 62 were determined to meet the criteria to be included in the review.

From these studies it was observed that, as the quality and quantity of available hardware has increased, the general variety and effectiveness of devices has increased accordingly. While older studies tended to use single-mode technologies, there is a growing trend in studies that incorporate devices able to provide multiple modes of feedback, which can be especially useful for individuals with visual impairments.

Although the hardware platforms in assistive technology are rapidly changing, the main applications of education, navigation, and computer accessibility have largely remained core issues for individuals who are visually impaired. In recent years, with the rise of assistive software, a larger emphasis has been placed on computer accessibility for visually impaired users, underscoring the need for them to interact and learn digitally.

While much progress has been made, many designs are not fully validated and tested by the intended user audience. Studies should include at least five users in order to collect qualitative data on a sufficient portion of usability issues, and more if statistical analysis on quantitative data is required (Nielsen & Landauer, 1993). While sighted users are not needed in all circumstances, they can be effectively used as a pilot group, a control group, or a secondary target audience, depending on the device.

Future research and development should intentionally focus on exploring promising hardware platforms and addressing the largest areas of need in the visually impaired community. It is expected that future technological developments will allow assistive devices to include increasingly responsive interfaces, capable of providing feedback to the user through multiple modalities.

In Table 1.5, recommendations for optimal device characteristics and general suggestions for structuring the design methodology of user studies are prescribed.

Optimal Device Characteristics	**Design Methodology Recommendations**
• Multimodal: providing both tactile and auditory feedback to the user is often most effective, especially for conveying complex information • Adaptable: utilizing simple and flexible platforms for a variety of different applications • Portable and affordable: using hardware platforms such as adapted touch screens or computers when possible as opposed to more expensive pin matrices and force feedback technologies • Refreshable: displaying new information rapidly and responsively • Multitouch: providing as many points of contact as possible and allowing the user to explore freely, ideally using both hands	• User-centered design: Employ an iterative design process, in which users are involved in every stage of the planning and prototyping process, to ensure the final design is best adapted to user needs. • Usability testing: Test the device with at least five users with visual impairments to identify significant usability issues. • Large sample size: Test with a larger group of users with visual impairments if statistically significant results are required, or if the device will have many different applications. • Sighted users: Include blindfolded sighted users in the study design to serve a clearly defined purpose, such as a pilot group or a control group.

Table 1.5: Summary of recommendations for future research.

Developments in assistive technology also offer numerous benefits to individuals without visual impairments, as they can offer feedback through multiple modes and provide innovative strategies for all people to access complex sources of information more efficiently and effectively. As educational technology plays a prominent role in the classroom, and computer accessibility becomes an increasingly universal necessity, these application areas will be the most important to address. Finally, design should be centered upon users' needs, and developers should make it a priority to validate all devices with sufficient feedback from users with visual impairments. User-centered design processes, which include feedback from users in each step of the design process, should be used whenever possible.

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Chapter II: A User-Centered Design and Analysis of an Electrostatic Haptic Touchscreen System for Students with Visual Impairments[2]

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Abstract

Students who are visually impaired face unique challenges when learning mathematical concepts due to the visual nature of graphs, charts, tables, and plots. While touchscreens have been explored as a means to assist people with visual impairments in learning mathematical concepts, many devices are not standalone, were not developed with a user-centered design approach, and have not been tested with users who are visually impaired. This research details the user-centered design of an electrostatic touchscreen system for displaying graph-based visual information to individuals who are visually impaired. Feedback from users and experts within the visually-impaired community informed the iterative development of our software. We conducted a usability study consisting of locating haptic points in order to test the efficacy and efficiency of the system and to determine patterns of user interactions with the touchscreen. The results of the usability study showed that: 1) participants correctly located haptic points with an accuracy rate of 69.83% and an average time of 15.34 seconds out of 116 total trials, 2) accuracy increased across trials, 3) efficient patterns of user interaction involved either a systematic approach or a rapid exploration of the screen, and 4) haptic elements placed near the corners of the screen were more easily located. These results indicated that our user-centered design approach resulted in an intuitive interface for people with visual impairments and laid the foundation for demonstrating this device's potential to depict mathematical data shown in graphs.

Keywords: Haptic, Visual impairment, Blind, Assistive technology, User-centered design, Electrostatic, Mathematics, Touchscreen, Education.

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[2] Has been submitted to the International Journal of Human-Computer Interactions.

Introduction

In 2013, approximately 694,000 school-aged individuals in the United States reported some level of visual disability (Erickson et al., 2014). According to the 2014 federal quota census data, 61,739 students are eligible for adapted educational materials through the Act to Promote the Education of the Blind. While some of these students attend schools specifically dedicated to those who are blind, many are educated in the mainstream school system, which are frequently ill-equipped with adequate assistive technologies (American Printing House for the Blind, 2015).

For students who are visually impaired, math and science concepts pose a unique challenge due to the visual nature of data embedded in graphs, charts, tables, and plots (Nam et al., 2012). Tactile models such as embossed paper and pin boards with yarn are often used to present these ideas to visually impaired students; however, the translation from the visual to the tactile domain results in a loss of information (Smith and Smothers, 2012). Although more complex solutions such as the Talking Tactile Tablet have been used in classrooms for testing purposes, they rely solely on audio output, are not easily refreshable, and limit user interaction to a finite set of buttons (Landau et al., 2003).

In contrast to tactile technologies, haptic feedback mechanisms have been used for a variety of different applications since the 1960s, with initial research directed towards assisting people with visual impairments (Israr et al., 2014). For instance, the Optacon used input from an optical sensor to actuate an array of vibrating pins so that an individual could feel and interpret written text (Linvill and Bliss, 1966). Another device, the Tactile Television, converted camera images of basic shapes into an array of vibrating points

(Collins, 1970). These initial studies on haptic assistive technology were a precursor to an influx of research in the field of surface haptics.

Recent haptic devices, such as the Marvel Avengers Vybe Haptic Gaming Pad, are commercially driven and have focused on enhancing the user experience of neurotypical individuals (Israr et al., 2014). However, some researchers have attempted to use haptic technologies to address the unique needs of people who are visually impaired. In spite of this effort, a significant portion of published research about tactile and haptic assistive devices did not include user testing at all or only included testing with sighted individuals, indicating the lack of a user-centered design approach (Horton et al., 2016).

Electrostatics, a subfield of haptics, focuses on the development of haptic effects by applying voltages to a conductive surface in order to create friction on a user's finger. Strong and Troxel pioneered the development of electrostatic haptic technology when they created a tactile display by applying different voltages to an array of pins in order to produce texture (1970). Recently, researchers at Disney have continued this work by developing the TeslaTouch touchscreen device (Bau et al., 2010), which was analyzed as a tool to aid the visually impaired (Xu et al., 2011). This particular study included three participants who were totally blind and indicated that various representations of shapes have differing levels of effectiveness in conveying information. Specifically, participants were able to identify a solid shape at almost twice the rate of outline-only or solid-with-outline representations. The TeslaTouch system is novel but inherently unfeasible for personal use, as it requires the user to be connected via a wrist strap and the device to be connected to a personal computer.

Other touchscreens have been explored as potential solutions to assist people with visual impairments in learning mathematical concepts. Toennies et al. combined haptic and auditory modalities using a Series 1000 TouchSense Demonstrator device, and reported 66% success rates when sighted users were asked to navigate to specified Cartesian coordinates[3]. In a shape recognition task, users had difficulty discriminating shapes from one another, which the authors hypothesized was due to the variety of exploration methods utilized (2011). In a follow-up study with updated hardware (Samsung Galaxy Tab 7.0) and users with visual impairments, the 66% navigation success rate was reproduced. However, when users were asked to identify the coordinates of given points, no combination of haptic/auditory grid and points yielded over 75% success (Gorlewicz et al., 2014).

This research aimed to extend the work by Gorlewicz et al. by: 1) investigating the role of exploration strategies in successful interpretation of haptic signals and 2) isolating the haptic sensory channel to optimize that modality prior to integrating auditory features. We adopted a user-centered approach to the design of an electrostatic touchscreen system that provides graphical information to individuals with visual impairments. In addition, we conducted a usability study consisting of a haptic localization task in order to test the efficacy and efficiency of the system and to determine patterns of user interactions with the touchscreen.

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[3] Although the hardware used in this study is mechanically-actuated as opposed to electrostatically controlled, the texture generated through both methods produces a vibrotactile effect.

A User-Centered Design Approach

The user-centered approach was dependent upon feedback in the form of interviews with assistive device experts and preliminary tests with users with visual impairments. Figure 1 depicts the iterative design process, which alternated these feedback sessions with hardware and software development.

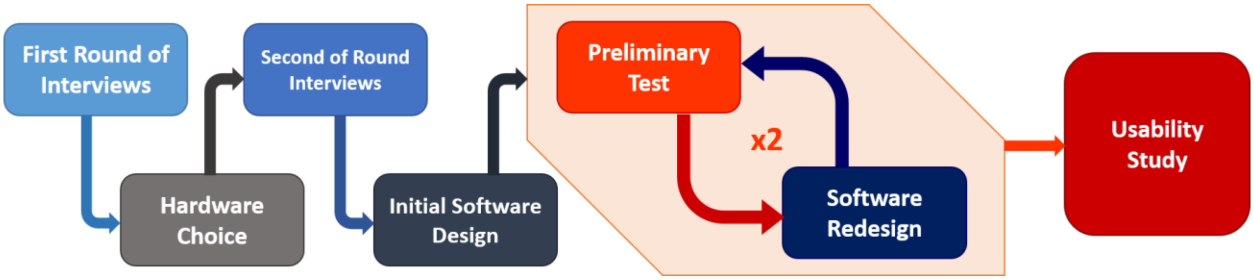

Figure 2.1: User-centered design process. Illustration of methodological steps taken to design and test an electrostatic assistive system.

First Round of Interviews

The design initially focused on identifying the technological needs of students with visual impairments and their educators. The intent was to determine which hardware and software features are highly regarded among commercially available educational assistive devices. Therefore, we conducted a series of interviews with experts from the National Federation of the Blind (NFB), the International Braille and Technology Center for the Blind (IBTC), and the Maryland School for the Blind (MSB). Based on the results of the interviews, we selected an electrostatic hardware platform.

A visit to the IBTC was conducted to learn about current trends in assistive technologies for people with visual impairments, and the primary challenges faced by users of these systems. The interview with the manager revealed that although several devices had strong graphical precision, their general cost and bulkiness prevented them from being popular among the visually impaired community. The common concerns included: 1) the size and cost of the high-tech devices, 2) the cross-compatibility problems caused by the many types of assistive devices and their various operating systems, and 3) the dependency of devices on host computers, rendering them non-portable.

At the MSB, the principal, vice-principal, and two teachers unanimously reported that mathematics was the most difficult subject to teach to students with visual impairments. They currently use Swell Touch Paper, Wikki Stix, and the Draftsman Tactile Drawing Board (see Figure 2), but find that these tools provide neither immediate (speed of creating the first graphic) nor refreshable (ability and speed of creating subsequent graphics) interfaces. Graphs must be individually composed by hand or printed onto non-reusable paper, and are therefore not flexible or quickly adaptable to the students' learning needs. Despite their limitations, these low-tech media were preferred by teachers over higher-tech devices like the IVEO tablet, which reportedly took 1.5 hours per graph to program. The educators identified refreshability, ease of programming, and intuitive display of information as essential qualities of assistive devices.

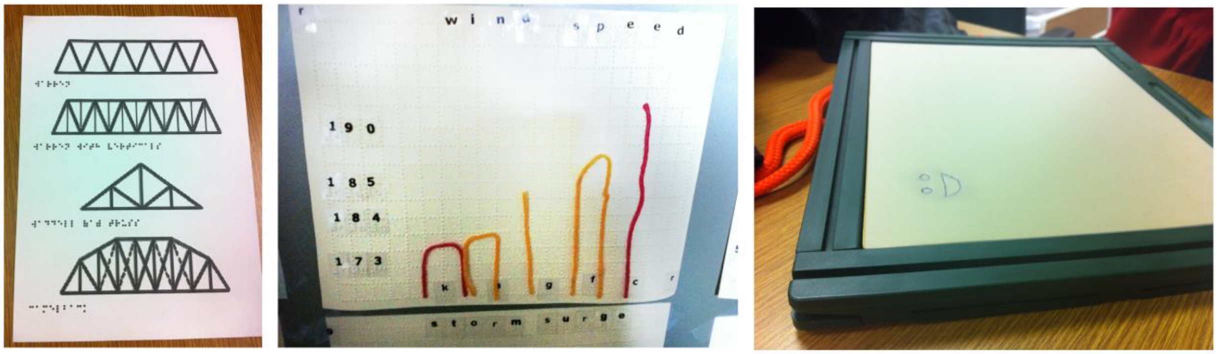

Figure 2.2: Traditional assistive technologies. Images of (left) Swell Paper; (center) Wikki Stix, and (right) the Draftsman Tactile Drawing Board used at the Maryland School for the Blind (MSB).

The educators also noted concerns about the design of educational assistive devices for classroom use. One of the essential missions of the MSB is to prepare students to be integrated into mainstream classrooms, but these classrooms have a number of limiting factors such as small desk sizes, lack of computers at workstations, and lack of one-on-one instruction for students with visual impairments. Therefore, they recommended that assistive devices be small, function independently of a host computer, run on battery power, and provide enough feedback for independent learning.

The educators also detailed two opposing problems in the field of graphical accessibility devices. First, there is a need to transfer as much information as possible from the visual to the tactile domain to counteract the information loss inherent in the transfer process. On the other hand, there is also a need to simplify the tactile representation to avoid sensory overload. New technologies must be carefully developed to balance these two needs. One way to address the aforementioned information loss in tactile and haptic graphics is to provide additional multimodal information. The educators recommended using primarily auditory stimuli, supplemented by tactile and visual information.

Based on the first round of interviews, it became clear that an ideal system should be portable, freestanding, and affordable; have a powerful and commonly-used operating system; and have an intuitive, multimodal user interface. To achieve these goals, an electrostatic haptic touchscreen system was chosen to be tested.

Hardware Choice – Tanvas Electrostatic Haptic Touchscreen

The chosen device incorporates a haptic touchscreen developed by Tanvas[4]. The electrostatic touchscreen covers half of a 10.6 inch screen of a Microsoft Surface Pro 2 (Figure 3) and has a resolution of 208 pixels per inch. The device was constrained to a single point of contact (i.e. a user can only explore the touchscreen with a single finger at a time).

The system outputs a haptic effect once every four milliseconds. The intensity of the effect at any given time is controlled by an integer taking a value between zero (no haptic output strength) and 254 (maximum haptic output strength), with the value 255 reserved as an off state. There are two types of haptic effects: a) temporal haptic effects, which are generated by iterating through an array of intensities such that the effect varies over time, and b) spatial haptic effects, which are generated by mapping static integer values to each pixel on the screen such that the effect varies by location. Both of these effects can be used to create textures that, once applied to a certain area of the screen, make a haptic object. The electrostatic touchscreen has a 14 pixel touch resolution, so a haptic effect must be applied over at least a 14 pixel diameter to ensure the effect will be perceived by the user. If an effect is placed over fewer than 14 pixels, a user is less likely to perceive it.

Overall, this hardware addressed many of the recommendations made by the experts during the first round of interviews. In particular, the Tanvas device is 7”x11.5’’, easily fits on any size desk, has a rechargeable battery, and can serve as a standalone computer because it runs the Windows 8.1 operating system. The device also supports

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[4] www.tanvas.co

multimodal output (haptic, visual, and auditory). Additional interviews were then conducted to inform the preliminary software design choices.

Figure 2.3: Tanvas electrostatic touchscreen. Microsoft Surface Pro with Tanvas touchscreen overlay.

Second Round of Interviews

An expert-user interview was conducted with a Senior Staff Engineer at the National Library Service for the Blind and Physically Handicapped, who is totally blind. This individual was selected primarily because of his personal and professional experience with the use of assistive technologies.

When asked about necessary and desired software features, the interviewee suggested providing orientational and positional information and maintaining consistency in the presentation of haptic features. For instance, the edges of the touchscreen provide constant spatial orientation. The interviewee also suggested that important UI features be static (remain in a fixed location on the screen) to promote ease of user navigation.

The interviewee reported his personal experience in college-level math classes, in which the greatest challenges arose not from the difficulty of the mathematical concepts but from the increasingly complex visuals associated with them. In particular, the lack of refreshable devices meant that in order to access a tactile version of a graph shown in class, he had to wait multiple days and pay a peer to draw it on embossed paper. While he easily understood the basic components which make up graphs, the combination of graphical components into a cohesive image is perceptually challenging. The interviewee's personal difficulties with understanding graph-based concepts informed our decision to focus our software development and preliminary test on the various subcomponents of graphs.

Initial Software Design

The initial software design had three goals: 1) to promote ease of programming and administering lessons for a sighted teacher, 2) to investigate static UI features that provide spatial orientation for the user, and 3) to create the software for the first preliminary test.

In order to meet the needs of the educators at the MSB, a tool for teaching lessons was built in the form of a haptic slideshow, in which each slide contains any number of haptic images. This allowed teachers to navigate through slides one at a time via forward and backward navigational buttons, so users could feel each image at their own pace. Additionally, to address the teachers' frustrations with having to painstakingly program lessons into devices, the software was designed to support the rapid creation of commonly used mathematical objects like circles, lines, and rectangles.

Secondly, a feature to help users with visual impairments find static UI elements was implemented. Specifically, a single haptic circle, named the Home Button, was created to serve as a test UI button for users with visual impairments. When the user held their finger over the Home Button, the device would beep three times before the button was activated. Because this feature served two purposes (to act as a UI button and to provide spatial orientation information) the Home Button was intentionally positioned in the center of the screen. This location was chosen because it was furthest from all edges and corners of the device, suggesting that the most useful spatial orientation information could be communicated by centering the Home Button.

Finally, in preparation for the first preliminary test, we embedded new haptic objects into the slideshow. Specifically, we added objects that comprise components of a graph such as dots, circles and regular polygons, lines of varying thicknesses, and graph axes. Shapes had two styles of haptic representation: 1) a haptic effect within their whole area, and 2) a haptic effect only on their outline. Additionally, though unprompted by the previous interviews, we decided to implement and test user preference of three different textures. These included: 1) Granite, a temporal effect Tanvas designed to feel like granite, 2) PeakAndGradient, a temporal effect we designed to create peaks and valleys in intensity, and 3) HexHole, a temporal effect we designed to feel like a mesh of strong intensities with regular gaps.

Preliminary Test 1

A first preliminary test was conducted with an adult male who is totally blind, holds a Ph.D. in Mathematics, and served as the treasurer of the Science and Engineering Division at the NFB. Based on his feedback, parallel prototypes for a variety of software features were developed.

The user was presented with ten slides of randomly-generated shapes all using the Granite texture: five filled followed by five outlined. While he performed equally well at identifying filled and outlined shapes, he reported that the outlined shapes were much more difficult to identify, and attributed his success to having gained experience from the filled shapes. The circles were difficult to identify due to their lack of distinguishing angles, while the triangles were easiest to identify due to their acute angles. Each additional side made the shape harder to correctly identify. For example, when presented with an octagon, the user believed it to be a circle, and maintained that the two were indiscernible even upon correction.

The user was then shown three slides that each consisted of two small and filled squares which were side by side and had different textures. For each slide, he was asked to describe the difference between the two paired textures and identify which one he preferred over the other. In analyzing the three textures shown, the user had no consistent preference and insisted that all three were too weak for him to feel well.

To determine the preferred thickness of a line, we created a single slide with eight parallel vertical lines of decreasing thickness. The user could detect only the thickest five lines, which ranged from 38 pixels to 10 pixels in thickness. He reported that 38 and 30 pixel lines were far too thick to represent lines, and his preferred lines were 14 and 10 pixels thick.

Finally, the user freely discussed design choices and recommendations. His primary feedback was the need for multitouch capabilities (multiple fingers in contact with the screen simultaneously), which would allow him to use one finger as a point of reference and another for exploration. However, the Tanvas device was limited to a single point of contact at that time. To help correct for this, he suggested points of reference such as menu buttons, which were also mentioned in our expert-user interview. After being shown the Home button, he believed the bottom and the corners of the screen to be the best place for such UI buttons, and appreciated the auditory cues that it produced when touched. He also believed that auditory information would greatly strengthen the effectiveness of the device, as being told what shape he was feeling made it much easier to trace it. When asked if audio should be incorporated as a primary or secondary means of information transfer, he suggested to initially test only the haptic effects. He reasoned that the superiority of multimodal devices is well-established, so it is best to optimize the haptics independently in order to ensure that the strength of the device can be attributed to the haptics.

Software Redesign 1

The first software redesign was motivated by three primary recommendations: 1) to create stronger haptic textures, 2) to make the corners of shapes more pronounced, and 3) to determine the optimal thickness of a haptic line.

In order to create the strongest possible texture, the upper limits of the device’s frequency and amplitude capabilities were analyzed. It is known that the optimal frequency for vibration detection falls between 200 and 300 Hz (Mortimer et al., 2007). The frequency output of the Tanvas device was then maximized to 125 Hz by using only two intensity values: 0 and 254. These intensities were selected to maximize the amplitude of the haptic signal, so we named the texture MaxAmp.

The participant from the first preliminary test cited the corners of shapes as their key distinguishable features, so two approaches were defined to improve the identifiability of corners. First, the haptic effect near corners was strengthened by applying the MaxAmp texture to the vertices of shapes and the Granite texture to the rest of the shape. However, we did not include this haptic method in the second preliminary test because it did not help identify corners when tested by members of the research team. Second, auditory feedback in the form of a clicking noise was created which was produced when the user’s finger crossed over a vertex. Testing the audio-haptic solution with the software developers proved highly successful. However, the decision was made to not test the auditory feedback method because of the participant's warning about audio eclipsing haptics as the primary modality.

Finally, a smaller range of line thicknesses was tested based on the responses of the first preliminary participant. A decision was made to use the three thicknesses that he deemed neither too thick nor too thin: 20, 14, and 10 pixels. In addition, lines that were 18, 16, and 12 pixels thick were included to allow for greater specificity.

Preliminary Test 2

We conducted a second round of testing with the same expert user in order to determine whether the re-design addressed his initial recommendations. The second preliminary test was a similar but slightly refined version of the first preliminary test. The user was asked to feel seven filled shapes and seven outlined shapes, randomly generated from a list of circle, triangle, square, pentagon, hexagon, heptagon, and octagon. Similar to the first preliminary test, heptagons and octagons were indiscernible from circles, triangles were again the easiest to identify, and the participant strongly preferred filled over outlined shapes.

Next, side-by-side comparisons of squares of texture were presented, this time with every pairwise combination of the four available textures. Of the textures presented, Granite and MaxAmp were preferred over PeakAndGradient and HexHole. However, the participant again found all textures weaker than he would have preferred.

The refined set of vertical line thicknesses was presented in order to determine which was ideal for haptically portraying lines. The participant's preferred thickness was 20 pixels, which is slightly thicker than the preferences of the first preliminary participant. Based on the expert recommendations, a second round of design changes was made.

Software Redesign 2

Based on the continued superiority of filled shapes, outlined shapes were entirely discarded. The canonical line thickness was set at 20 pixels, due to both preliminary test participants recognizing it as an adequate thickness, and one participant being unable to perceive the thinner lines preferred by the other. When creating more complex graphical elements such as axes and function curves, we maintained this line thickness. While the development of haptic representations of these other graphical elements continued, for the purpose of the usability study, we made the decision to focus solely on the users' ability to locate small haptic circles on the device.

The haptic effects shown in the preliminary tests were quite limited in comparison to the full range of software features developed. The aforementioned line thickness was used to determine the optimal length of a tick mark on an axis, which was in turn used to determine the optimal diameter of a dot which would be placed on a coordinate system. We chose a diameter of 120 pixels for a haptic dot and selected to fill these haptics dots with the MaxAmp texture based on the feedback from both participants. The decision to limit the study to single-texture haptic dots allowed for a more thorough exploration of the general usability of the haptic device and the optimal locations for static user interface features.

Usability Study

To better understand how users experience the electrostatic touchscreen system, we conducted a usability study consisting of a number of trials of a simple localization task using only the haptic modality. The primary metrics studied were accuracy (rate of correctness in responses) and efficiency (time between initial contact with the device and verbal response). We developed a series of specific aims in order to verify and evaluate the effectiveness of our design choices at accomplishing our previously stated goals. The aims of the study were: 1) to determine whether accuracy changed across trials, 2) to determine whether efficiency changed across trials, 3) to analyze the strategies by which participants explored the screen, and 4) to determine whether the location of each dot on the screen significantly affected accuracy.

Participants

Participants were recruited from the National Federation of the Blind of Maryland and the Maryland School for the Blind. The inclusion criteria were: minimum age of eight years old, visual impairment of at least legal blindness as defined by the World Health Organization, and absence of neurological or physical disabilities beyond blindness. The demographics and visual impairment of all participants are summarized in Table 1. All participants included on this study were also required to pass three cognitive tasks that tested their ability to: 1) verbally count from zero to ten, 2) differentiate a straight line from a sinusoidal curve, and 3) distinguish dots from dashes. All adult participants gave informed consent, and a parent or legal guardian of each child gave his/her informed consent based on the procedures approved by the University of Maryland's Institutional Review Board (IRB).

	Participant ID											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Gender	M	F	F	M	M	F	M	M	F	F	M	F
Age	17	16	20	9	14	12	10	11	9	40	15	50
Visual Impairment Level	B	B	S	B	B	S	B	B	B	B	T	T

Table 2.1: Demographics of participants. Visual impairment levels were categorized into S - Severe Visual Impairment (20/200 - 20/400), B - Blindness (20/400 - 20/1200), and T - Total Blindness (No Light Perception).

Methods

Each participant was blindfolded to ensure that visual stimuli do not affect performance. The protocol consisted of 30 slides displayed on the device, each with a single haptic dot measuring 120 pixels in diameter and located at one of 30 evenly spread, predetermined locations on the screen. The participants were asked to locate the dot on the screen with their finger and verbally affirm that they had found it. The participant was given 45 seconds per slide to complete the task before being prompted for a response or allowed to give up. The response accuracy and the time elapsed from initial contact with the screen to verbal response were recorded with a video camera. If at any point, five consecutive dots were correctly identified by the user, the test concluded, as the participant was deemed to have mastered the task. Video analysis was used to confirm response and time, as well as to analyze the strategy used to explore the screen.

Results and Discussion

Of the 116 total trials completed, participants correctly located the dot with an accuracy rate of 69.83% and an average time of 15.34 seconds. 11 of the 12 participants correctly identified 5 dots in a row within the 30 dots allotted, with the 12th choosing to withdraw from the study after 25 trials.

Specific Aim 1: Accuracy Analysis

In order to determine whether accuracy rate changed across trials, each participant's trials were partitioned into quintiles (five even partitions, with extra trials in the earlier quintiles in the case of unevenness). The quintiles adjust for the difference in the number of completed trials across participants. The overall accuracy rate for each quintile was determined by averaging the quintile accuracy across participants. Additionally, the single participant who did not master the task within 30 trials was removed to find the average quintile accuracy across participants who gained mastery of the task. The quintile accuracy data can be found in Table 2.

Quintile Number	Avg Accuracy (All)	Avg Accuracy (Mastery)
1	0.775	0.573
2	0.733	0.736
3	0.963	0.959
4	0.829	0.886
5	0.967	1.000

Table 2.2: Average *quintile accuracy.* Average accuracies across quintiles including all participants (center) and only including those who mastered the task (right).

A linear regression analysis of the average accuracies for every participant resulted in an R^2 value of 0.500, as shown in the left graph in Figure 4. A linear regression analysis of the average accuracies for only those who mastered the task resulted in an R^2 value of 0.816 and is shown in the right graph in Figure 4.

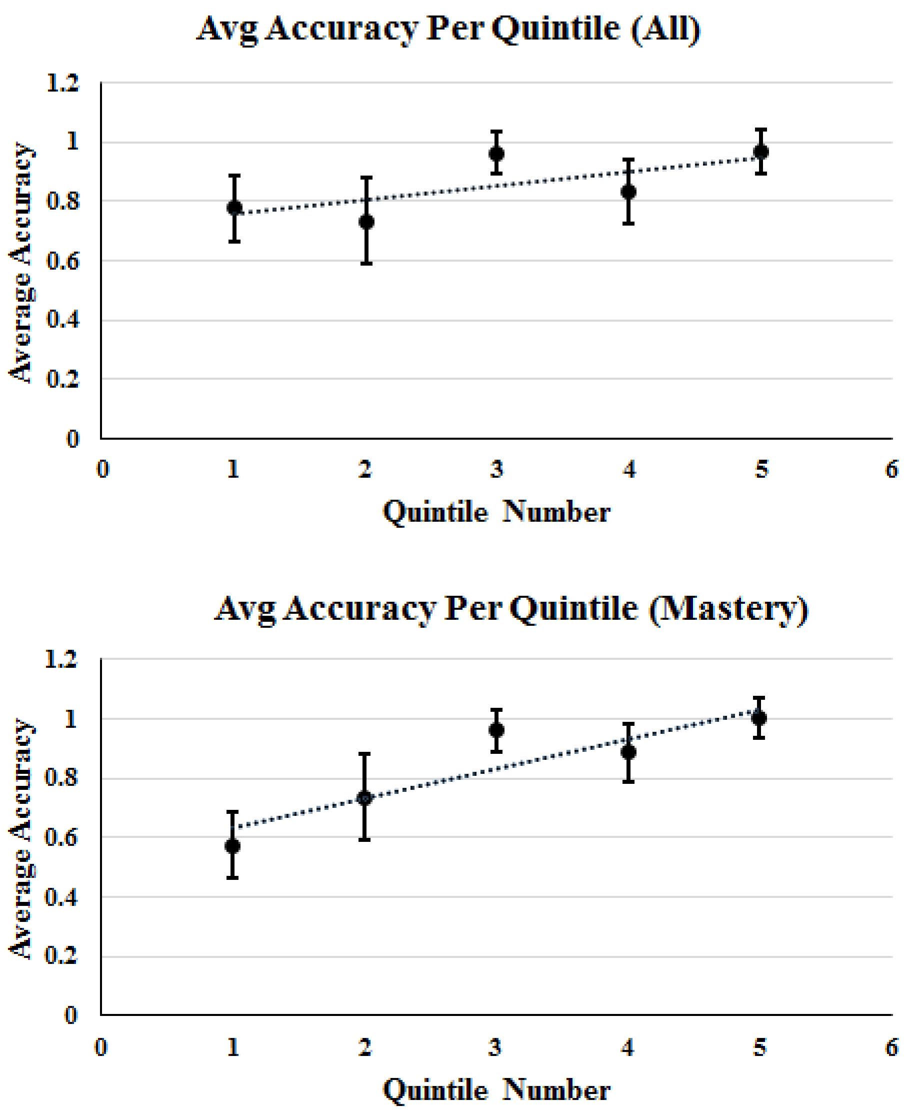

Figure 2.4: Linear regression of quintile accuracy. Linear regression of average accuracies across quintiles including all participants obtained an R^2 value of 0.4048 (top) and when only including those who mastered the task obtained an R^2 value of 0.5734 (bottom). The error bars represent the standard error of the mean for each quintile.

A t-test of the slope of the regression line was used to determine if there is a significant relationship (alpha = 0.05) between quintile and accuracy. We obtained a p-value of 0.18, indicating no significant relationship between trial number quintiles and average accuracy. However, upon removing the single participant who did not correctly identify 5 dots in a row, we obtained a p-value of 0.04, indicating that there is indeed a significant relationship between trial number quintiles and the accuracy of response for the participants who gained mastery of the device within 30 trials.

Of the 12 participants, 11 gained mastery of the simple haptic tasks within 30 trials, with the average participant only needing 8.27 trials to do so. In addition, these 11 who showed a basic understanding of the haptic representations also exhibited a learning curve, as evidenced by the p-value of 0.04. These results indicate that most people with visual impairments can perform simple tasks using an electrostatic touchscreen and can rapidly improve in their performance on the task.

Specific Aim 2: Efficiency

In order to determine whether efficiency changed across trials, each participant's trials were again partitioned into quintiles. The overall efficiency rate for each quintile was calculated by averaging the quintile efficiency across participants. The quintile efficiency data can be found in Table 3.

Quintile Number	**Avg Time in seconds (All)**	**Avg Time in seconds (Mastery)**
1	14.425	13.845
2	14.067	12.727
3	11.725	10.591
4	14.467	12.455
5	10.733	10.545

Table 2.3: Average quintile efficiency. Average efficiencies across quintiles including all participants (center) and only including those who mastered the task (right).

Linear regression analysis of the efficiency for every participant resulted in an R^2 value of 0.405, as shown in the left graph in Figure 5. Linear regression analysis of the average time for those who mastered the task resulted in an R^2 value of 0.573 as shown in Figure 5.

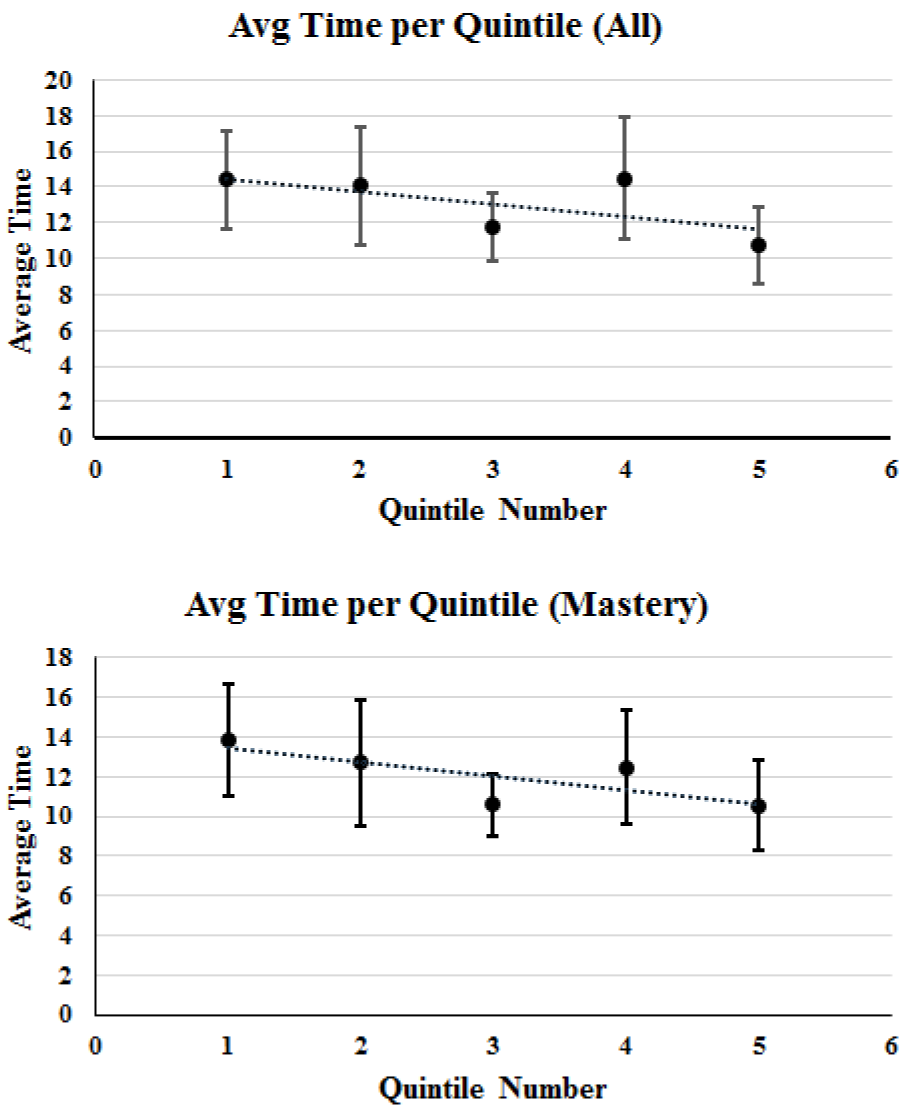

Figure 2.5: Linear regression of quintile efficiency. Linear regression of average efficiencies across quintiles including all participants obtained an R^2 value of 0.4048 (top) and only including those who mastered the task obtained an R^2 value of 0.8158 (bottom). The error bars represent the standard error of the mean for each quintile.

A t-test of the slope of the regression line was used to determine if there is a significant relationship (alpha = 0.05) between quintile and efficiency. We obtained a p-value of 0.25, indicating no significant relationship. With the same single participant removed, the p-value changed to 0.14, still indicating no significant relationship.

The linear regression showed no significant improvement in efficiency, however the lack of improvement does not affect the general usability of the system, which is primarily designed to transfer graphical information to users accurately rather than quickly. Therefore, improved efficiency is less important than improved accuracy, especially in light of the extended time which students with accommodations for their visual impairments are typically afforded (American Foundation for the Blind, n.d.).

Specific Aim 3: Strategy Analysis

In order to analyze the strategies used by participants to explore the electrostatic touchscreen, we first used the process of iterative coding to determine four strategies: 1) systematic sweeping motions, 2) attempted sweeping motions with significant gaps, 3) rapid unstructured screen exploration with a focus on corners, and 4) no discernible strategy (Figure 6). The average accuracy rate for each strategy can be found in Table 4. Due to the limited number of participants in each category, these results have been limited to descriptive statistics.

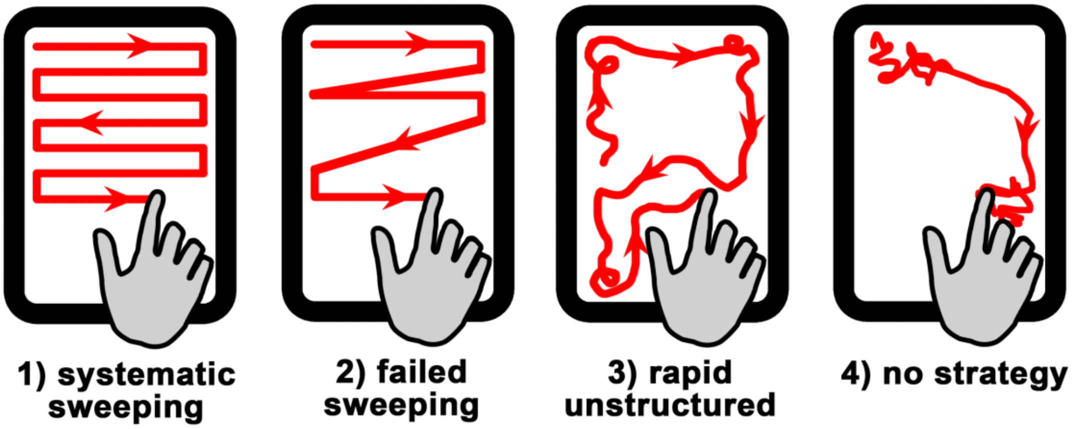

Figure 2.6: Exploration strategies. Visual depictions of four exploration strategies, from systematic back and forth sweeping to no discernable strategy.

Strategy	**Number of Participants**	**Average Accuracy Rate**
Systematic Sweeping	2	0.917
Failed at Systematically Sweeping	4	0.739
Rapid Unstructured Screen Exploration	4	1.000
No Discernible Strategy	2	0.735

Table 2.4: Average accuracy for exploration strategy. Different strategies used by participants (left), the number of people who used each strategy (center), and the average accuracy rate for each strategy (right).

In examining the four strategies and their respective accuracy rates, we can see that 50% of participants intuitively used a strategy which yielded an accuracy rate of over 90%, which we deem highly successful. The systematic sweeping strategy was expected to be successful due its methodical nature, but rapid unstructured screen exploration with a focus on corners was surprisingly effective (100% accuracy across four participants). We attribute the success of this strategy to three factors: 1) locating the corners at the beginning of every trial allows the user to spatially reorient themselves and ensure coverage of the full length and width of the screen 2) rapid motion results in higher coverage of the screen in a shorter period of time when compared to slower motion 3) rapid motion of the contact point on the screen enhances the perception of friction. Among participants who did not perform one of the two highly successful strategies, 66% attempted and failed to execute the systematic sweeping strategy. Given that the intuition of using a systematic strategy is not lacking, additional feedback from the device informing participants if they have overlooked parts of the screen is likely to improve the execution of this strategy. Additionally, for users who do not intuitively use one of the highly effective strategies, we believe that these strategies can be taught via auditory output from the device or the assistance of an instructor, though this claim requires additional research.

Specific Aim 4: Location-Based Accuracy Analysis

In order to determine whether the location of the dot on the screen affected the cross-participant accuracy rate for that dot, we calculated the average accuracy rate for each slide which was completed by at least five participants. Again, the analysis is limited to descriptive statistics. As seen in Figure 7, the accuracy rates for dots in the corners of the screen tended to be higher than those for dots nearer to the center of the screen. Additionally, 11 of the 12 participants had higher average accuracy rates on those three corner dots than they did on all dots. While the results do not necessarily indicate poor accuracy in the middle of the screen, they do indicate relatively high accuracy on the corners (over 80%). These findings corroborate the assertions of our two preliminary participants, who stated that the corners of the screen were the best for static UI elements such as a home or menu button.

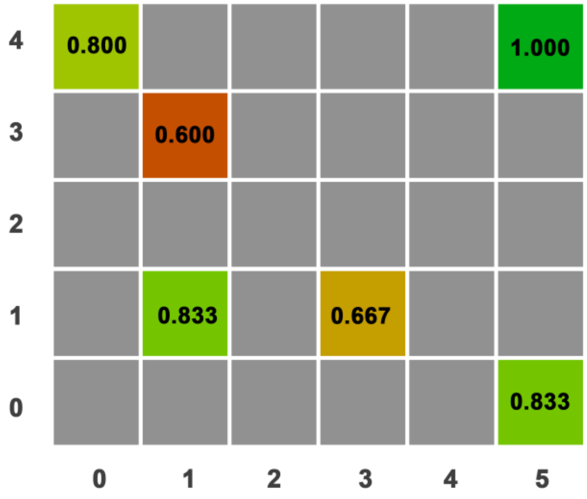

Figure 2.7: Accuracy heatmap. Heatmap of accuracy rates for screen locations completed by at least five participants.

Conclusion and Future Directions

Prior research about haptic accessibility devices for people with visual impairments frequently does not take a user-centered approach in the investigation of desired features and functionalities or the testing process itself. The research described in this paper differs from and improves upon the existing literature in the following ways: 1) the device in this study is a portable, standalone system with a powerful operating system, 2) we received feedback from a larger and more varied group of users, all of whom have profound visual impairments, and 3) we implemented an iterative, user-centered design process in order to develop an assistive device which is optimized for people with visual impairments. The findings from the usability study, coupled with the desirable features of the hardware platform, show promise that the user-centered design approach results in a usable, accessible, and intuitive device for people with visual impairments.

We note three future directions which should be pursued based on the findings of this research. The first goal is to test the device's usability in regards to increasingly complex mathematical concepts. We have developed haptic representations of lines, axes, and points in Cartesian space, and created a protocol for testing these graphical concepts. The second goal is to integrate multimodal output in order to create a more complete system which can be used independently by people with visual impairments. Specifically, we wish to determine whether auditory feedback can be used to teach effective strategies to users or to correct behaviors such as the failed systematic sweeping motion. The third goal is to enable multiple points of contact with the touchscreen, which was universally requested by the MSB educators and preliminary test participants. With improvements to the hardware and firmware to enable multitouch, future research is required to determine the impact of improved spatial awareness on performance of complex haptic tasks.

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Chapter III: A Haptic Approach to Depicting Mathematical Concepts on an Electrostatic Touchscreen[5]

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Abstract

Introduction: Various technologies, including electrostatic touchscreens, have utilized haptic feedback to present information to individuals with visual impairments. This study aimed to investigate the usability of an electrostatic haptic device designed to assist individuals with learning basic mathematical graph elements.

Method: Twelve participants with varying degrees of visual impairment were asked to perform several tasks on a Tanvas electrostatic touchscreen. The tasks included: locating haptic dots on the screen, determining orientation of lines, understanding counting schemes of number lines, and integrating these skills in order to understand a Cartesian coordinate system. The accuracy of answers and response time were measured to determine the effectiveness of the device in portraying visual information and the users' efficiency in using the device.

Results: Participants who met a baseline for device use exhibited a statistically significant increase in accuracy across trials of the dot localization task ($p=0.04$). Participants also exhibited a statistically significant increase in efficiency ($p=0.000$) in determining the x- or y-coordinate of a dot in Cartesian space, while the accuracy remained constant across trials. Five of six increasingly complex tasks yielded an average accuracy over 0.50, with three above 0.68.

Discussion: Participants were shown to understand haptic depictions of dots and axes by completing tasks with an improvement in accuracy or efficiency. Limitations in the representations of straight lines and overlapping haptic objects render tasks involving spatial orientation or object differentiation difficult for users with visual impairments.

Implications for Practitioners: Data from simplistic tasks indicate that the hardware and software are generally effective in conveying graphical information to people with visual impairments. The electrostatic touchscreen exhibits promise as an assistive device for displaying visual mathematical elements through the haptic modality.

Keywords: Haptics, Visually Impaired, Learning, Mathematics.

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[5] Has been submitted to the AFB Journal of Visual Impairment and Blindness (JVIB).

Introduction

According to the American Printing House for the Blind, there are 694,000 school-aged individuals with visual impairments in the United States (Erickson, Lee, & von Schrader, 2014). Of the 61,739 who are eligible for adapted educational materials, 83% are taught in the general education environment, which is often not equipped with adequate educational tools for the visually impaired (American Printing House for the Blind, 2015). These students tend to fall behind in courses and curricular activities related to STEM subjects (Beck-Winchatz & Riccobono, 2008) due to the largely visual nature of graphs, charts, and tables, as well as the prevalence of spatial concepts such as position, orientation, and scale (Nam, Li, Yamaguchi, & Smith-Jackson, 2012).

Educators often use tactile models to present graphical mathematical information to students with visual impairments. Simple, manipulable materials, such as Swell Touch Paper and Wikki Stix, provide a cost effective and intuitive way to depict visual concepts (Instructors at the Maryland School for the Blind, personal communication, November 11, 2013). However, each graphic must be created anew because the materials are not reusable. More complex assistive devices, such as the Talking Tactile Tablet, are refreshable and often incorporate auditory feedback. Despite advances in the field of tactile technologies, the translation from the visual domain to the tactile domain inherently results in a loss of information (Smith and Smothers, 2012).

Haptic technology, which adds kinesthetic feedback to tactile information, has been applied to assistive devices to mitigate this information loss. One such technology, a touchscreen developed at Vanderbilt University, proved effective in displaying points on a Cartesian plane using a combination of haptic and auditory feedback (Toennies, Burgner, Withrow, & Webster, 2011; Gorlewicz, Burgner, Withrow, & Webster, 2014). Though this research is promising, it is preliminary in nature, as it tests only three users with visual impairments and is limited to fairly simple mathematical tasks. A systematic literature review evaluating a number of haptic or tactile assistive devices found that a significant portion of existing research did not include user testing with the visually impaired community (Horton et al., 2016). The research presented in this paper extends the existing literature by evaluating an assistive haptic device with a large and varied population of users who are blind or visually impaired.

This study aimed to investigate the usability of an electrostatic haptic device to assist individuals with visual impairments in learning basic mathematical graphical elements. Specifically, a series of increasingly complex graph-based tasks were designed to assess the accuracy and efficiency with which participants perceive mathematical graphics on the device.

Methods

Participants

Participants were recruited from the National Federation of the Blind of Maryland and the Maryland School for the Blind. The requirements for inclusion were: minimum age of eight years, visual impairment of at least legal blindness as defined by the World Health Organization, and absence of neurological or physical disabilities beyond blindness. Twelve individuals, six male and six female, participated in the study. Two participants were totally blind and 10 were legally blind. The participants' ages ranged from nine to 50 years old, with nine under the age of 18. A summary of the participants' demographic information is presented in Table 3.1. All participants included in the study were also required to pass three cognitive tasks that tested their ability to: (1) verbally count from zero to 10, (2) distinguish a straight line from a sinusoidal curve, and (3) distinguish dots from dashes. All adult participants gave informed consent, and a parent or legal guardian of each child gave his/her informed consent based on the procedures approved by the University of Maryland Institutional Review Board (IRB).

	Participant ID											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Gender	M	F	F	M	M	F	M	M	F	F	M	F
Age	17	16	20	9	14	12	10	11	9	40	15	50
Visual Impairment Level	B	B	S	B	B	S	B	B	B	B	T	T

Table 3.1: *Demographics of participants.* Visual impairment levels were categorized into S - Severe Visual Impairment (20/200 - 20/400), B - Blindness (20/400 - 20/1200), and T - Total Blindness (No Light Perception).

Device

The device consists of a Tanvas electrostatic touchscreen overlaid onto half of a 10.6 inch Microsoft Surface Pro 2, as shown in Figure 3.1. By applying voltages underneath the touchscreen, the device causes the user to sense friction while moving their finger across the surface. By varying the applied voltage, it is possible to manipulate the resulting texture perceived by the user. The touchscreen has a 14 pixel touch resolution, which means that in order to be certain that the effect will be perceived by a user, a haptic effect must be applied to at least a 14 pixel diameter. The system is also constrained to a single point of contact, restricting participants from touching the screen with more than one finger at a time.

Figure 3.1: *Microsoft Surface Pro with Tanvas touchscreen*.

Procedure

During the experiment, each participant completed the protocol individually. The participant was introduced to the device, told to only touch the screen with one finger at a time, and given time to become familiarized with the device's size and shape without haptic effects displayed. Once the participant was accustomed with the device, they were blindfolded to ensure that visual stimuli did not affect their performance. The participant was then asked to perform a total of six sequential tasks as depicted in Figure 3.2. The tasks tested the individual's ability to identify, interpret, and integrate increasingly complex components of mathematical graphs. Tasks 3-5 were completed with a horizontal number line and then repeated with a vertical number line. Due to the screen dimensions, the horizontal number line had six equally spaced tick marks whereas the vertical number line had five tick marks.

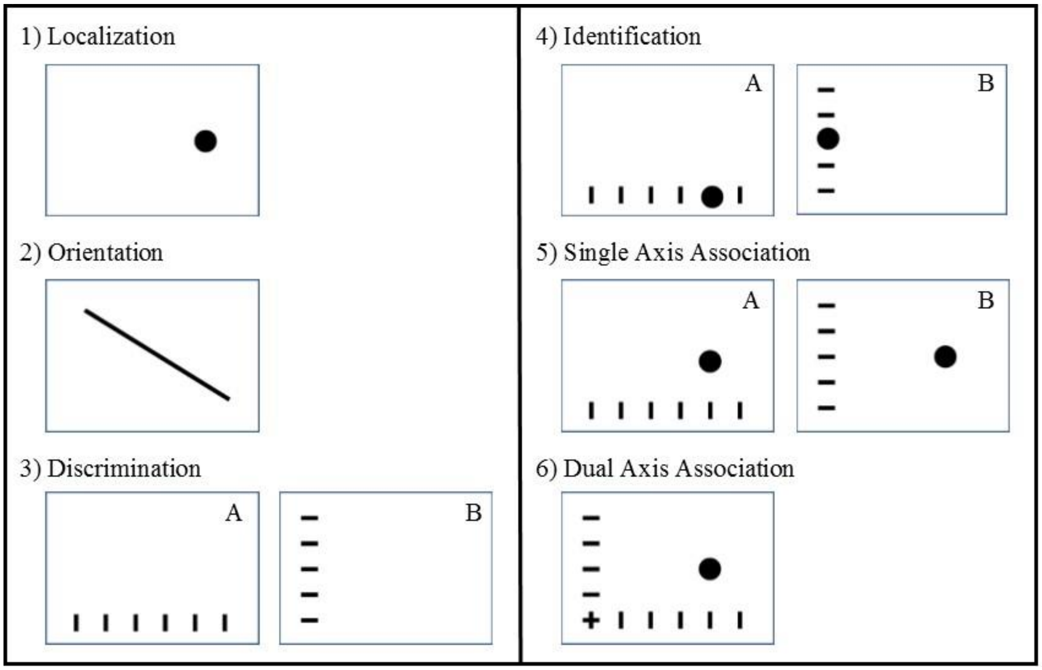

Figure 3.2: *Tasks in Usability Study.* Illustration of the six tasks provided to the participants on the Tanvas touchscreen during the testing session. Note: Dots, dashes, and lines indicate the presence of haptic effect.

Task 1: Localization

This task consisted of 30 trials in which a haptic dot (a circle 120 pixels in diameter) located at one of 30 evenly-spaced, predetermined locations on the screen was presented (Figure 3.2.1). The participant was asked to locate the dot on the screen and verbally confirm finding it. The accuracy of the response and the response time (the number of seconds between initial contact with the screen and the verbal response of the participant) were recorded. If the participant did not respond within 45 seconds, they were prompted for a response or allowed to give up and proceed to the next trial. If the participant could not locate the dot on the first trial, it was used as a “training example” and the administrator led the participant’s finger over the dot to recognize it. The training example was not included in analyses. If at any point, five dots in a row were correctly located, the Localization task concluded, as the participant was deemed to have mastered it. If a participant failed to correctly localize five consecutive dots within 30 trials, they were dismissed from the study. Video recordings were used to confirm response accuracy and time.

Task 2: Orientation

The orientation task consisted of ten trials, each with a single straight line (20 pixels thick) positioned either horizontally, vertically, or diagonally across the screen (Figure 3.2.2). The participant was given 60 seconds to verbally categorize the line as horizontal, vertical, or diagonal. The responses and response time were recorded. If 60 seconds elapsed, the participant was prompted for a response.

Task 3: Discrimination

First, to prepare for the task, a horizontal number line with six equidistant tick marks was positioned along the bottom of the screen (Figure 3.2.3). The participant was informed that the leftmost tick mark was “tick zero” and that subsequent tick numbers increased in number by one. They were asked to trace the number line and count aloud to determine the number of the last tick mark. The participant was then told that the last tick mark was “tick five” and given time to recount the ticks until comfortable with this numbering scheme. When necessary, the participant was reminded to begin counting tick marks from “zero” for the duration of the study.

The participant then began the discrimination task. There were 5 trials in which the participant was given 60 seconds to find a specific tick number (e.g. “tick 3”) and verbally assert finding it. Each participant received the same series of randomized ticks. The response and response time were recorded. This procedure was repeated using a vertical number line (Figure 3.2.3) positioned on the left side of the screen.

Task 4: Identification

This task consisted of ten trials, each with a horizontal number line along the bottom of the screen and a dot superimposed over one of the tick marks (Figure 3.2.4). The participant was given 60 seconds to determine the number of the tick on which the dot was located. The response and response time were recorded. This procedure was repeated using a vertical number line (Figure 3.2.4).

Task 5: Single Axis Association

This task consisted of 20 trials, each with a horizontal number line along the bottom of the screen and a dot located at varying heights directly above one of the tick marks (Figure 3.2.5). The participant was given 60 seconds to locate the dot, verbally acknowledge finding it, and state the tick number above which the dot was located. The responses and response time were recorded. These procedures were repeated with dots located to the right of a vertical number line (Figure 3.2.5).

Task 6: Dual Axis Association

This task consisted of 20 trials, in which both a horizontal and a vertical number line were presented on the screen, representing the first quadrant of the Cartesian plane. A single dot was displayed at one of 30 predetermined locations, corresponding to the coordinate system (Figure 3.2.6). The participant was given 120 seconds to locate the dot, verbally acknowledge finding it, and then state the tick numbers on the horizontal and vertical number lines to which the dot corresponded. The responses and response time were recorded.

Data Analysis

Responses for all trials were evaluated in terms of two variables: accuracy and efficiency. Accuracy was primarily coded on a binary scale. For Tasks 3-6, wherein the response was a numerical answer corresponding to a number line, an intermediate accuracy value of 0.5 was assigned to responses within one unit of the correct answer. For Task 6, the accuracies of the horizontal and vertical coordinates were averaged together for each trial. For each task, efficiency was determined by the time in seconds from initial finger contact with the screen to the verbal response of the participant.

To determine whether accuracy and efficiency changed across trials of Task 1, each participant's trials were grouped into quintiles (five even partitions, with extra trials placed in the earlier quintiles in the case of unevenness). The quintiles adjust for the difference in the number of completed trials across participants and were used to evaluate how participants progressed in accuracy and efficiency.

The overall accuracy for each quintile was determined by averaging the accuracy scores across participants. Linear regressions were used to determine if there was a significant relationship between quintile number and average accuracy, as well as quintile number and average efficiency. In order to check for outliers among the participants, the regressions were repeated excluding the one participant who did not gain mastery of the baseline Localization task.

For Tasks 2-5, a fixed-effects model was used to test if there was a significant relationship between trial number and accuracy as well as trial number and efficiency within each participant's responses. Participants who completed less than 5 trials in any task were excluded from that regression.

For Tasks 3-5, which were presented in both a horizontal and vertical orientation, accuracy and efficiency were calculated by averaging the corresponding horizontal and vertical trials. To validate the assumption that Tasks 3-5 could each be analyzed as a single, averaged data set despite half of the trials being conducted on a horizontal number line and half on a vertical, paired t-tests ($p \leq 0.05$) were used to test for differences between each participant's average time and accuracy in the horizontal and vertical orientation. No significant differences were found between horizontal and vertical orientations for any of the tasks.

Six of the total participants withdrew from Task 6. As a result, data analysis for Task 6 has fewer trials than previous tasks. Average accuracy and response time for all tasks are included in Table 3.2.

Results

Table 3.2 provides a summary of average accuracy and efficiency for all participants on each task.

	Average for All Participants	
Task	**Accuracy**	**Time (s)**
Localization	0.70	15.34
Orientation	0.48	18.93
Discrimination	0.84	8.82
Identification	0.52	19.50
Single Axis Association	0.68	21.86
Dual Axis Association	0.54	27.73

Table 3.2: Summary of average accuracy and efficiency for each task.

In Task 1, a significant relationship was observed between trial quintile and accuracy but not between quintile and efficiency. While the first task was originally designed to be used as a baseline to confirm that all participants were physically able to feel the haptic feedback, it yielded useful information on participants' progress as they initially learned to use the device. The average quintile accuracy and efficiency for all participants are shown in Figure 3.3.

Linear regression analysis of accuracy data yielded no significant relationship between quintile and accuracy (p=0.18) when including all participants, but showed a significant correlation between quintile and accuracy (p=0.04) when analyzing the eleven participants who mastered the task. This result suggests that the single participant who did not master the task was likely an outlier. With respect to efficiency, neither the regression including all participants nor the regression including only participants who gained mastery yielded statistically significant findings (p=0.25 and p=0.14 respectively).

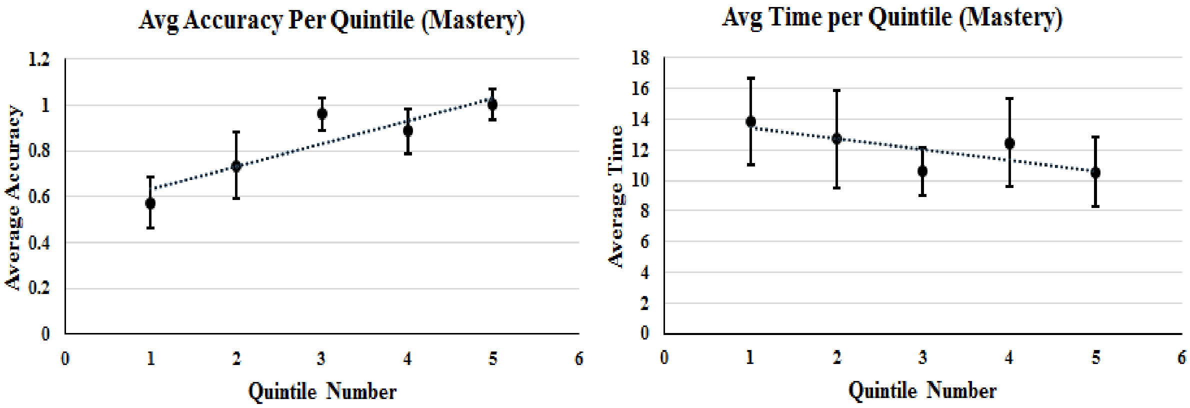

Figure 3.3: Average accuracy and time by quintile for participants who gained mastery of the Localization task. Error bars indicate the standard error for each mean.

No significant relationship was found between trial number and accuracy or efficiency for Tasks 2-4. This is likely due to the relatively low number of trials per participant in each of these tasks, yielding low statistical power.

Task 5 required participants to integrate the components they had learned in the previous sections in order to interpret graphical mathematical information. A fixed-effect regression analysis showed a significant change in time by trial number (β = -0.95 sec/question, p=0.000) indicating that task efficiency increased across trials (Figure 3.4) while the regression over the accuracy data (Figure 3.5) yielded no statistically significant findings (p=0.995). Therefore, the data suggested that participants became more efficient in completing the task without showing loss in accuracy.

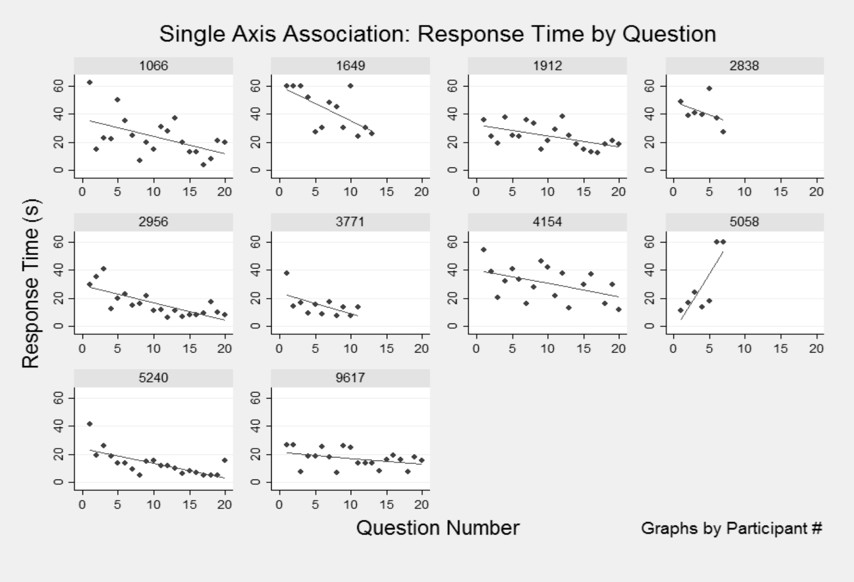

Figure 3.4: Single Axis Association: Response time by question. Individual participant plots of response time (averaged between horizontal and vertical sections) vs. question number for Single Axis Association tasks.

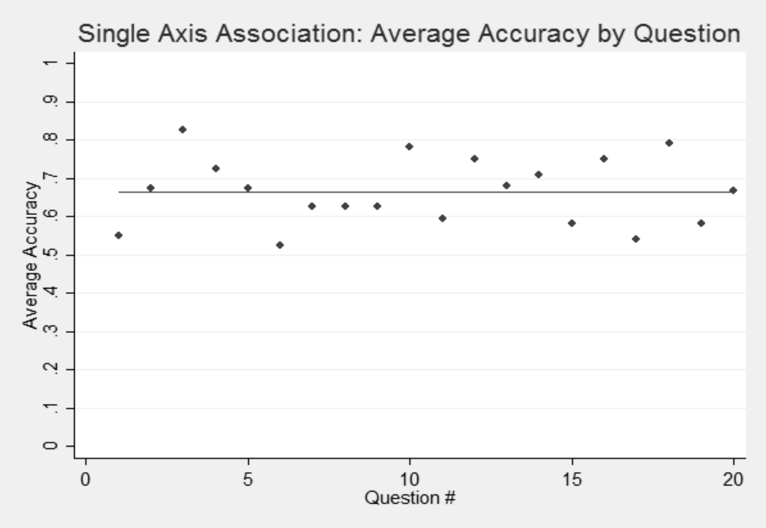

Figure 3.5: Plot of average accuracy vs. question number on Single Axis Association tasks for all participants combined.

Discussion

There is a notable separation in the average accuracy across tasks, with three tasks above 0.68 and three below 0.54. The tasks with high average accuracy, namely Localization, Discrimination, and Single Axis Association, consisted of non-overlapping haptic objects. This implies that the representations of graphical elements are comprehensible when presented independently of one another.

The Orientation, Identification, and Dual Axis Association tasks had relatively lower average accuracies. The Orientation task required participants to trace haptic lines to determine their orientation, and yielded an average accuracy of 0.48. The electrostatic effect is perceived more strongly by moving across the line rather than along it because of the greater distinction between textured and non-textured areas. However, participants intuitively traced along a given line to complete this task which may explain the low accuracy exhibited.

The Identification task, in which users identified a dot superimposed over a tick mark on the number line, yielded an average accuracy of 0.52. Upon analysis of video recordings, it was observed that participants frequently passed their fingers over the dot without detecting it. In addition, multiple participants verbally noted that dots and ticks were indistinguishable. This implies that the difference in thickness between the two haptic objects was not sufficiently substantial. This finding is corroborated by the higher accuracy of the Single Axis Association task, which does not have any overlapping haptic objects.

The average accuracy on the Dual Axis Association task was 0.54. However, it was anticipated that the accuracy on Dual Axis Association would be lower than the accuracy on Single Axis Association due to the high complexity of this task. Additionally, participants who attempted the task reported that they found the axes usable in two dimensions.

Conclusion and Future Work

The results presented in this paper suggest that electrostatics have the potential to be an effective medium for depicting mathematical graphics to students with visual impairments. Participant mastery of the Localization task shows that most users were able to perceive the electrostatic haptic effect and became more accurate in completing the task. Furthermore, the participants' level of accuracy on the Single Axis Association and Dual Axis Association tasks suggests that the Tanvas hardware platform is effective in conveying position of points on a plane and that users are able to understand spatial relationships between haptic objects on the screen. Findings in both the Localization and Single Axis Association tasks indicate that users improved in performance as they gained experience within those tasks.

Additional research is required in order to improve upon the electrostatic representations of lines and overlapping objects, as well as to mitigate the limitations of this hardware system. Here, we provide three primary recommendations. First, the haptic representations of lines and overlapping objects must be modified in order to find intuitive, understandable depictions. For overlapping objects, we recommend the exploration of multiple distinct haptic textures, which may help users distinguish between objects more effectively. Second, multitouch capabilities should be developed in order to determine whether multiple points of reference improve understanding of haptic objects. The ability of users with visual impairments to complete spatially complex tasks should be reevaluated with a multitouch-enabled electrostatic touchscreen. Third, multimodal output should be enabled in the form of auditory and visual feedback. The superiority of multiple modalities has been well-documented (Turk, 2014), and will allow the device to be more usable in classroom settings or for independent use.

The electrostatic touchscreen adapted in this study has been shown to effectively present mathematical concepts of increasing complexity to individuals with visual impairments. Ultimately, electrostatics show promise as a foundation for educational assistive technologies for students with visual impairments.

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Conclusion

The specific aims of this research were to analyze literature concerning the design and testing of tactile technologies, develop an electrostatic touchscreen system for the purposes of portraying mathematical graphical information to individuals with visual impairments, and test the usability of this system via a series of increasingly complex tasks.

A systematic literature review was conducted in order to establish the foundations for designing and implementing new technologies to meet the needs of individuals with visual impairments. Based on past literature, certain characteristics were determined to be desirable in both the design and testing of assistive technologies for individuals with visual impairments. The proposed optimal device characteristics included multimodality, adaptability to different applications, portability, and refreshability. Ideally, methodological design should include a user-centered development approach as well as usability testing within the visually impaired community.

An electrostatic touchscreen system was developed following the guidance of the systematic literature review. In particular, the implementation of a user-centered design approach led to an iterative process of applying expert feedback to software redesigns in an attempt to optimize the device for use by individuals with visual impairments. Interviews were conducted with experts from the National Federation of the Blind (NFB), the International Braille and Technology Center for the Blind (IBTC), and the Maryland School for the Blind (MSB). Based on the recommendations of these experts, the Tanvas electrostatic touchscreen overlay was chosen as the hardware platform. After the initial design of basic haptic software features, a series of preliminary tests led to the development of a full usability study protocol.

The usability study investigated whether the system could effectively convey haptic information to users with visual impairments. The study aimed to assess the participants' accuracy and efficiency in a series of increasingly complex graphical tasks. Participants showed improvement in accuracy in locating haptic objects, as well as increased efficiency when spatially relating haptic objects on the screen. The results demonstrated the basic usability of electrostatic haptic touchscreens by individuals with visual impairments. Additionally, the device's portability and refreshability made it ideal for use in academic settings, both on its own merits and when compared to currently available alternatives.

While this research shows promise for the usability of such a device, there is room for improvement in several key areas. The representation of certain haptic elements, such as straight lines and overlapping objects, should be further investigated in order to create more intuitively understandable features. Recent hardware developments have enabled multiple points of contact with the electrostatic touchscreen, underscoring the need for further usability testing. With this research validating the effectiveness of the haptic modality at conveying graphical information to users with visual impairments, the addition of multimodal output should improve the usability of the device in the classroom setting and for personal use.

The novelty and strength of this research stems from the following: 1) a thorough understanding of the desirable features of assistive devices, as obtained through a systematic literature review; 2) the iterative, user-centered design process, which afforded expert feedback from and user testing with members of the visually impaired community, and; 3) the extension of user testing beyond basic usability, resulting in insights on the effectiveness of the haptic modality at conveying complex graphical and spatial information to users with visual impairments.

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Appendix I: Glossary[6]

Accuracy: rate of correctness on a task

Assistive device/technology: broad term including assistive, adaptive, and rehabilitative devices used by people with disabilities

Blind: 20/400 - 20/1200 vision

Cognitive: related to conscious intellectual processes

Congenital (blindness): blindness from birth

Dot: 120 pixel diameter, single-textured, filled haptic circle

Electrostatics: a subset of vibrotactile haptic technologies in which the vibration is created by applying a voltage between a conductive surface within the touchscreen and the user's finger

Efficiency: time between initial contact with the device and verbal response for a task

Force feedback: a subset of haptic devices which apply an active force on the user (e.g. rumble packs)

Gamification: the application of typical elements of game playing to the process of usability testing

Granite: a temporal haptic texture, created via measurements of real-world granite

Haptic: tactile information combined with kinesthetic feedback

Haptic effect: the signal sent from the device circuitry to the touchscreen once every 4 milliseconds

Haptic object: a textured image, displayed on an electrostatic touchscreen

Haptic output strength: the intensity value of the haptic effect, which encodes amplitude of the voltage signal

HexHole: a temporal haptic texture designed to feel like a mesh of strong intensities with regular gaps

Iterative coding: the process of grouping qualitative feedback into distinct categories

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[6] These definitions were generated by the authors with reference to the Oxford English Dictionary.

Iterative design process: the cyclic process or prototyping, testing, analyzing, and refining a product or process

Mainstream (in reference to classroom): school classrooms not designed specifically for students with special needs

Mastery (in reference to Localization task): having located five haptic dots in a row in the Localization task

MaxAmp: a temporal haptic texture comprised of two values: 0 and 254. It maximizes the frequency and amplitude of haptic output on the electrostatic touchscreen

Mechanically-actuated haptics: a subset of vibrotactile haptic technologies in which the vibration is created via mechanical actuators

Modality: the primary sensory channel (e.g. auditory, tactile, visual) through which something is experienced or expressed

Multimodal: conveying information via more than one modality

Multitouch: the ability to perceive haptic effects from an electrostatic touchscreen with two or more fingers simultaneously

Neuroplasticity: the ability of a brain to reorganize its neurons to make new connections

PeakAndGradient: a temporal haptic texture designed to create peaks and valleys in intensity

Perception: the neurological interpretation of a sensation

Pin matrices: a class of assistive devices in which an array of pinpoints is manipulated to create a 3-dimensional image

Point of contact: the location of a finger on the electrostatic touchscreen

Preliminary test (in reference to Chapter 2): the initial testing phases of the user-centered design process, each of which was conducted with a user with visual impairments

Proprioceptors: sensors that provide information about joint angle, muscle length, and muscle tension, which is used to determine the position of the limb in space

Quintile: any of the five equal groups in which the trials of the Localization task were split

Refreshable: able to be updated in real time (e.g. in reference to a display screen or image)

Response time: time taken from initial contact with the screen to the verbal response of the participant, in seconds

Sensation: physical feeling resulting from contact with the body

Severe visual impairment: 20/200 - 20/400 vision

Slide: single image consisting of one or more haptic objects

Spatial haptic effect: haptic effects generated by mapping static integer values to each pixel on the screen such that the effect varies by location

Spatial information: information about the relative positions of haptic objects on the electrostatic touchscreen

Static UI features: elements on a user interface which remain in a constant position

Strategy (in reference to Chapter 2): the process by which a user explores the electrostatic touchscreen

Surface haptics: a superset containing vibrotactile devices, in which the user touches a solid surface on which haptic effects are generated

Swell Touch Paper: an adaptive technology which allows paper to be embossed for tactile purposes

Tactile: perceptible by the sense of touch

Temporal haptic effect: haptic effects generated by iterating through an array of intensities such that the effect varies over time

Texture: the perception produced by haptic effects on an electrostatic touchscreen

Tick: a filled, single-texture haptic rectangle with thickness 30 pixels starting 60 pixels above an axis and ending 60 pixels below an axis

Total Blindness: no light perception, worse than 20/1200 vision

UI feature: an element of a user interface, such as a button

Usability study: a systematic evaluation of a device by testing with target users. When referencing Chapter 2, this refers to the Localization task. When referencing Chapter 3, this refers to all six tasks.

User-centered design: a process wherein the needs and limitations of the users are consistently considered throughout every stage of the design process

Vibrotactile: the class of haptic technology which produces vibrations in order to create the perception of texture

Visual impairment: the decreased ability to see, which cannot be remedied by glasses

Wikki Stix: thin and flexible sticks made out of wax which are most commonly used by kids in art and crafts projects

Appendix II: Health Questionnaires

Adult Neurological Health Questionnaire

The sole purpose of this health questionnaire is to understand the health history of each participant. Private health information will not be identified in this study.

Have you ever… (Please circle yes or no)
1) Been seen by a neurologist or neurosurgeon? Yes No
    if yes, please explain____________________________________
2) Had a head injury involving unconsciousness? Yes No
    if yes, how long?_______________________________________
3) Required overnight hospitalization for a head injury? Yes No
    if yes, please explain?_______________________________________
4) Had any illness that caused a permanent decrease in memory or cognition? Yes No
    if yes, please explain____________________________________
5) Had a seizure? Yes No
    if yes, please explain____________________________________
6) Had any illness that caused a permanent decrease in motor ability (including speech)? Yes No
    if yes, please explain____________________________________
7) Had difficulty using your hands? Yes No
    if yes, please explain____________________________________

Please indicate your level of visual impairment based on the World Health Organization's levels of visual function listed below:

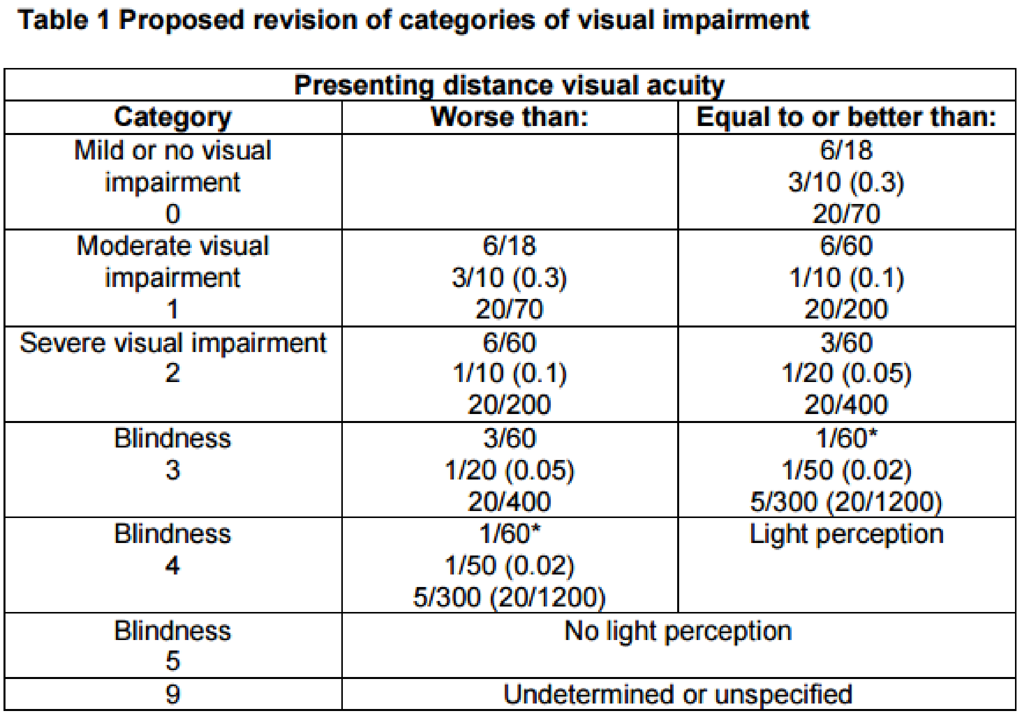

Table 1 Proposed revision of categories of visual impairment

Presenting distance visual acuity		
Category	**Worse than:**	**Equal to or better than:**
Mild or no visual impairment 0		6/18 3/10 (0.3) 20/70
Moderate visual impairment 1	6/18 3/10 (0.3) 20/70	6/60 1/10 (0.1) 20/200
Severe visual impairment 2	6/60 1/10 (0.1) 20/200	3/60 1/20 (0.05) 20/400
Blindness 3	3/60 1/20 (0.05) 20/400	1/60* 1/50 (0.02) 5/300 (20/1200)
Blindness 4	1/60* 1/50 (0.02) 5/300 (20/1200)	Light perception
Blindness 5	No light perception	
9	Undetermined or unspecified	

☐ Please check this box if you are not certain of the level of visual impairment

The above information is accurate to the best of my knowledge.

Signature of Participant________________________________

Printed Name of Participant___________________________

Signature of Witness__________________________________

Pediatric Neurological Health Questionnaire

The sole purpose of this health questionnaire is to understand the health history of each participant. Private health information will not be identified in this study.

Child's Name____
Sex___________ Age___________ Date of Birth___________

Past Medical History
Please list any prior major illnesses and/or injuries:

Birth History:
1) Any problems with the pregnancy? Yes No
if yes, what?____
2) Was your child born full term? Yes No
if no, how early?______________
3) Medical problems at birth? Yes No
if yes, what?____
Hospitalization/Surgery/Injury:
4) Except at birth, has your child been hospitalized? Yes No
if yes, list age(s) and reason_______________________________
5) Has your child ever had surgery? Yes No
if yes, list age(s), and reason_______________________________
6) Has your child ever had a head injury involving unconsciousness? Yes No
if yes, how long?_______________________________________
7) Has your child had any illness that caused a permanent decrease in memory or cognition? Yes No
if yes, please explain___________________________________
8) Had any illness that caused a permanent decrease in motor ability (including speech)?
if yes, please explain___________________________________

Review of Neurological Systems
Please circle yes or no to the following. Does your child have or has your child ever had… (if yes, please explain):
9) Seizure disorder? Yes No
____
10) Developmental delay? Yes No
____
11) Speech Delay? Yes No
____
12) Learning disabilities? Yes No
____

Please indicate your child’s level of visual impairment based on the World Health Organization’s levels of visual function listed below:

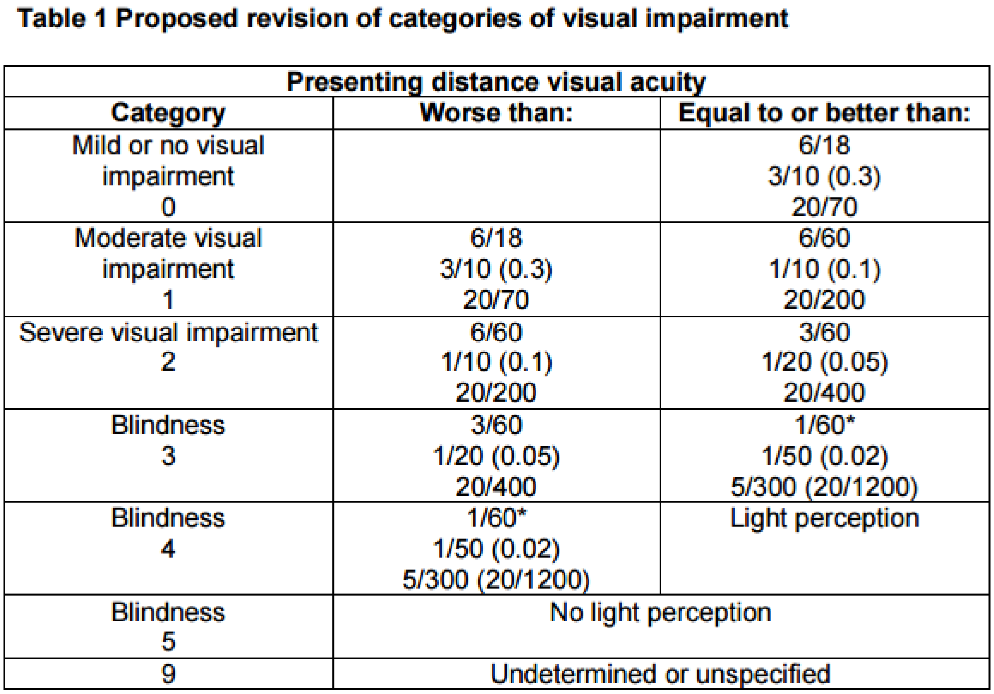

Table 1 Proposed revision of categories of visual impairment

	Presenting distance visual acuity	
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Mild or no visual impairment 0		6/18 3/10 (0.3) 20/70
Moderate visual impairment 1	6/18 3/10 (0.3) 20/70	6/60 1/10 (0.1) 20/200
Severe visual impairment 2	6/60 1/10 (0.1) 20/200	3/60 1/20 (0.05) 20/400
Blindness 3	3/60 1/20 (0.05) 20/400	1/60* 1/50 (0.02) 5/300 (20/1200)
Blindness 4	1/60* 1/50 (0.02) 5/300 (20/1200)	Light perception
Blindness 5	No light perception	
9	Undetermined or unspecified	

☐ Please check this box if you are not certain of the level of visual impairment

The above information is accurate to the best of my knowledge.
Signature of Parent or Guardian_______________________________

Printed Name of Parent or Guardian___________________________

Date________________

Appendix III: Assent and Consent Forms

Assent Form - For children

Dear Young Scientist,

Thank you for showing interest in our research. Before we begin, we would like you to read about the purpose of the study and the procedures that you will be following. Right now, you are either at the University of Maryland or at a convenient location selected by your parents. The reason for this study is to get a better idea of how to improve equipment that may be used to teach math to students.

Before you begin the study, your parent(s) will fill out a survey to find out if you have ever had difficulties thinking, moving or learning, or if you have ever had a serious head injury. This helps the researchers understand how your brain has grown and changed from when you were a baby until now. First, you will be asked a few questions to see how much you know about math. Afterwards, you will be asked to wear a disposable eye mask and participate in a session that lasts up to two hours. During the lesson, you may be using technology that you are familiar with, or technology that may be new to you. We will teach you how the technology works, and if you have any questions, feel free to ask them. After your participation, you will be awarded $40.00 monetary compensation.

It is important for you to know that you do not have to be in the study if you do not want to and can stop anytime for any reason. You may feel tired from paying careful attention during the study, and you may get a little bored during the lesson. However, you can talk to us at any time and ask for a rest break or you can stop the testing for any reason. Although there is no direct reward to you for being in our research project, your participation will help us to understand how to improve our technology so it's easier to use.

All data we collect from you will only be available to the researchers working on this study. Your records will be kept secret and will be stored in locked cabinets and/or on computers with special passwords in our laboratory. Any pictures, audio or videotapes taken will be shown to others only if your parents say it is okay.

If you have any questions now, or if you think of some later, please ask any of the researchers working with you.

Do you understand what we will ask you to do in this experiment and agree to be a part of our research?
If so, please state "Yes, I agree"

Researcher Signature ________________________________

Witness Signature ___________________________________

Project Title	**A Haptic Approach to Depicting Mathematical Concepts for Visually Impaired Students**
Purpose of the Study	This research is being conducted by Dr. Marcio Oliveira at the University of Maryland, College Park. We are inviting you to participate in the Exploratory Feedback phase of this research project. Your participation in our study will help with device calibration and usability by individuals with visual impairments. The purpose of this research project is to determine more effective techniques to teach mathematics to those who are visually impaired.
Procedures	You will be asked to come to the will be asked to come to the University of Maryland Division of Information Technology for one 30-minute session. During this session, you will identify various shapes using a device that the research group developed. The device is essentially a touch screen that gives the illusion of texture. You will be shown a series of slides, each showing a new haptic representation of shapes or graphical concepts in order to get quantitative and qualitative feedback for the effectiveness of the device.
Potential Risks and Discomforts	As a result of your participation in this study, you may experience a slight degree of fatigue from the concentration required during the performance of the Exploratory Feedback phase. To prevent fatigue, you may request a break at any time or may ask to withdraw from the session. There are no other known risks and no long-term effects associated with participation in this study.
Potential Benefits	Your participation is completely voluntary. The experiment is not designed to help you specifically, but it may have substantial impact on how to develop effective educational tools for visually impaired students in the classroom. You are free to ask questions or to withdraw permission for your participation at any time without penalty. You will be given a signed copy of this permission form and the investigators will provide you with the results of this study.
Confidentiality	All images and videos recorded in this study are anonymous and your name will not be identified at any time, should they be used for reports and presentations. All images and videos will be coded in a manner that protects your identity and will be stored in a locked cabinet or external hard-drive. Participants will be given an identification number so that it will not be linked with the data. Data will be archived minimally for three years following the duration of the experiment. When it is deemed no longer useful (up to a maximum of 10 years) it will be destroyed appropriately (e.g., shredding, deletion, etc). If we write a report or article about this research project, your identity will be protected to the maximum extent possible. Your information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law. If you feel the need to take a break from the study, you will be given time

	to rest for up to thirty minutes. If you wish to no longer participate in the study, you are permitted to do so.
Medical Treatment	The University of Maryland does not provide any medical, hospitalization or other insurance for participants in this research study, nor will the University of Maryland provide any medical treatment or compensation for any injury sustained as a result of participation in this research study, except as required by law.
Compensation	You will receive reimbursement for parking at the University of Maryland. Compensation will not be provided for participation in the Exploratory Feedback phase. You will be responsible for any taxes assessed on the compensation. ☐ Check here if you expect to earn $600 or more as a research participant in UMCP studies in this calendar year. You must provide your name, address and SSN to receive compensation. ☐ Check here if you do not expect to earn $600 or more as a research participant in UMCP studies in this calendar year. Your name, address, and SSN will not be collected to receive compensation.
Right to Withdraw and Questions	Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in the Exploratory Feedback phase, you may stop participating at any time. If you decide not to participate in the Exploratory Feedback phase or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify. If you decide to stop taking part in the Exploratory Feedback phase, if you have questions, concerns, or complaints, or if you need to report an injury related to the research, please contact the investigator: **Dr. Marcio Oliveira** **UMD | Building: SPH Building | Room: 2242-C** **301-405-2454 | Email: marcio@umd.edu**
Participant Rights	If you have questions about your rights as a research participant or wish to report a research-related injury, please contact: **University of Maryland College Park** **Institutional Review Board Office** **1204 Marie Mount Hall** **College Park, Maryland, 20742** **E-mail: irb@umd.edu**

	Telephone: 301-405-0678 This research has been reviewed according to the University of Maryland, College Park IRB procedures for research involving human subjects.	
Statement of Consent	Your signature indicates that you are at least 18 years of age; you have read this consent form or have had it read to you; your questions have been answered to your satisfaction and you voluntarily agree to participate in this research study. You will receive a copy of this signed consent form. If you agree to participate, please sign your name below.	
Signature and Date	**NAME OF PARTICIPANT (Please Print)**	
	SIGNATURE OF PARTICIPANT	
	DATE	

Project Title	**A Haptic Approach to Depicting Mathematical Concepts for Visually Impaired Students**
Purpose of the Study	This research is being conducted by Dr. Marcio Oliveira at the University of Maryland, College Park. We are inviting your child to participate in this research project because your child's participation in our study will help further research in mathematics education for the visually impaired. The purpose of this research project is to determine more effective techniques to teach visually impaired children mathematics.
Procedures	Prior to performance, you will complete a neurological health questionnaire for your child to ensure typical neurological development. You and your child will be asked to come to the University of Maryland for up to two sessions, within one month of each other. If you are unavailable to come to the University of Maryland, we will conduct a study at a location convenient for you. During the session, your child will be asked to complete a 10 minute pre-test, assessing your child's baseline understanding of graph-based math concepts. After this pre-test, your child, will be asked to wear a disposable eye mask and participate in a test on the device lasting up to two hours. The device is essentially a touch screen that gives the illusion of texture. If necessary, you and your child will be asked to come to the same location to finish the study. In total, your child will spend two hours maximum in our facilities.
Potential Risks and Discomforts	As a result of your child's participation in this study, your child may experience a modest degree of fatigue from the concentration required during the performance of the test and the lessons. To prevent fatigue, your child may request a break at any time or may ask to withdraw from the session. There are no other known risks and no long-term effects associated with participation in this study.
Potential Benefits	Your child's participation is completely voluntary. The experiment is not designed to help your child specifically, but it may have substantial impact on how to develop effective educational tools for visually impaired students in the classroom. You are free to ask questions or to withdraw permission for your child's participation at any time without penalty. You will be given a signed copy of this permission form and the investigators will provide you with the results of this study.
Confidentiality	All images, audio, and videos recorded in this study are anonymous and your child's name will not be identified at any time, should they be used for reports and presentations. All images, audio and videos will be coded in a manner that protects your child's identity and will be stored in a locked cabinet or external hard-drive. Participants will be given an identification number so that it will not be linked with the data. Data will be archived minimally for three years following the duration of the experiment. When it is deemed no longer useful (up to a maximum of 10 years) it will be destroyed appropriately (e.g., shredding, deletion, etc). If we write a report or article about this research project, your identity will be protected to the maximum extent possible. Your information may be

	shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law. If a child feels the need to take a break from the study, the child will be given time to rest for up to thirty minutes. If the time exceeds thirty minutes, the child should return another day. If the child wishes to no longer participate in the study, he or she is permitted to do so; however, compensation will not be given in full.
Medical Treatment	The University of Maryland does not provide any medical, hospitalization or other insurance for participants in this research study, nor will the University of Maryland provide any medical treatment or compensation for any injury sustained as a result of participation in this research study, except as required by law.
Compensation	After participation you will be awarded $40.00 monetary compensation. You will be responsible for any taxes assessed on the compensation. ☐ Check here if you expect to earn $600 or more as a research participant in UMCP studies in this calendar year. You must provide your name, address and SSN to receive compensation. ☐ Check here if you do not expect to earn $600 or more as a research participant in UMCP studies in this calendar year. Your name, address, and SSN will not be collected to receive compensation.
Right to Withdraw and Questions	Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in this research, you may stop participating at any time. If you decide not to participate in this study or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify. If you decide to stop taking part in the study, if you have questions, concerns, or complaints, or if you need to report an injury related to the research, please contact the investigator: **MARCIO A. OLIVEIRA** **4401B Computer and Space Sciences Building** **College Park, Maryland 20742** **301.405.5190 marcio@umd.edu**
Participant Rights	If you have questions about your rights as a research participant or wish to report a research-related injury, please contact: **University of Maryland College Park** **Institutional Review Board Office** **1204 Marie Mount Hall** **College Park, Maryland, 20742** **E-mail: irb@umd.edu** **Telephone: 301-405-0678**

University of Maryland College Park

	This research has been reviewed according to the University of Maryland, College Park IRB procedures for research involving human subjects.	
Statement of Consent	Your signature indicates that you are at least 18 years of age; you have read this consent form or have had it read to you; your questions have been answered to your satisfaction and you voluntarily agree to participate in this research study. You will receive a copy of this signed consent form. If you agree to participate, please sign your name below.	
Signature and Date	**NAME OF CHILD PARTICIPANT (Please Print)**	
	NAME OF PARENT/LEGAL GUARDIAN (Please Print)	
	SIGNATURE OF PARENT/LEGAL GUARDIAN	
	DATE	

Principal Investigator: Dr. Marcio Oliveira

Video Consent Form

PERMISSION FORM-for video, audio and image illustration purposes

University of Maryland, Cognitive Motor Neuroscience Laboratory

Identification of Project

Evaluating a Tactile Approach to Depicting Mathematical Graphics for Visually Impaired Students

Purpose of this form

Often, in sharing information about our research, it is useful to include images, audio and/or video clips from testing sessions with participants. Examples of such cases include: (1) poster and podium presentations at scholarly meetings and conferences, (2) scientific publication, (3) instructional purposes, and (4) on our internet site. The use of such images assists in a number of ways, particularly in validating our protocols, gathering data on the details of the tool-use interaction, and demonstrating the safety of our testing environment. These images will be used solely for illustration purposes.

In this form, we seek your permission to use images recorded for these purposes. Below, you will see a number of options. Please place your initials next to each option indicating that you are willing to allow.

Confidentiality

All images, audio and videos recorded in this study are anonymous and your name will not be identified at any time, should they be used for reports and presentations. All images, audio and videos will be coded in a manner that protects your identity and will be stored in a locked cabinet or external hard-drive. Participants will be given an identification number so that it will not be linked with the data. Data will be archived minimally for three years following the duration of the experiment. When it is deemed no longer useful (up to 10 years) it will be destroyed appropriately (e.g., shredding, deletion, etc).

Your information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.

If you feel the need to take a break from the study, you will be given time to rest for up to thirty minutes.

If you wish to no longer participate in the study, you are permitted to do so.

Statement of Permission

Videos, audio and images are recorded for the confidential records of this project in the Cognitive Motor Neuroscience Laboratory. Below are your intentions regarding their use:

___ You are willing to allow use of the images/audio for inclusion in presentation at scholarly meetings and conferences.

___ You are willing to allow use of the images/audio for inclusion in scientific publications.

___ You are willing to allow use of the images/audio for instructional purposes, including courses taught in the Department of Kinesiology at the University of Maryland

___ You are willing to allow use of the images/audio for inclusion in the Department of Kinesiology website at the University of Maryland available for public viewing

___ You are willing to allow use of the images/audio only for internal laboratory purposes.

Principal Investigator	Dr. Marcio Oliveira (PI), 4401B Computer and Space Sciences Building College Park, Maryland 20742 301.405.5190 marcio@umd.edu

Name of Participant: ____

Signature of Participant: ____

Today's Date: ____

If you have questions about your rights as a research subject or wish to report a research-related injury, please contact: Institutional Review Board Office, University of Maryland, College Park, Maryland, 20742; (email) irb@umd.edu; (telephone) 301-405-0678

Video Parental Permission Form – for child participant

PERMISSION FORM-for video, audio and image illustration purposes

University of Maryland, Cognitive Motor Neuroscience Laboratory

Identification of Project

Evaluating a Tactile Approach to Depicting Mathematical Graphics for Visually Impaired Students

Purpose of this form

Often, in sharing information about our research, it is useful to include images, audio, and/or video clips from testing sessions with participants. Examples of such cases include: (1) poster and podium presentations at scholarly meetings and conferences, (2) scientific publication, (3) instructional purposes, and (4) on our internet site. The use of such images/audio assists in a number of ways, particularly in validating our protocols, gathering data on the details of the tool-use interaction, and demonstrating the safety of our testing environment. These images will be used solely for illustration purposes.

In this form, we seek your permission to use images, audio, and video recorded with your child for these purposes. Below, you will see a number of options. Please place your initials next to each option indicating that you are willing to allow.

Confidentiality

All images, audio and videos recorded in this study are anonymous and that your child's name will not be identified at any time, should they be used for reports and presentations. All images, audio and videos will be coded in a manner that protects your child's identity and will be stored in a locked cabinet or external hard-drive. Participants will be given an identification number so that it will not be linked with the data. Data will be archived minimally for three years following the duration of the experiment. When it is deemed no longer useful (up to 10 years) it will be destroyed appropriately (e.g., shredding, deletion, etc).

Your information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.

If a child feels the need to take a break from the study, the child will be given time to rest for up to thirty minutes. If the time exceeds thirty minutes, the child should return another day.

If the child wishes to no longer participate in the study, he or she is permitted to do so; however, compensation will not be given in full.

Statement of Permission

Videos, audio and images of your child are recorded for the confidential records of this project in the Cognitive Motor Neuroscience Laboratory. Below are your intentions regarding their use:

___ You are willing to allow use of the images/audio for inclusion in presentation at scholarly meetings and conferences.

___ You are willing to allow use of the images/audio for inclusion in scientific publications.

___ You are willing to allow use of the images/audio for instructional purposes, including courses taught in the Department of Kinesiology at the University of Maryland

___ You are willing to allow use of the images/audio for inclusion in the Department of Kinesiology website at the University of Maryland available for public viewing

___ You are willing to allow use of the images/audio only for internal laboratory purposes.

Principal Investigator

MARCIO A. OLIVEIRA
4401B Computer and Space Sciences Building
College Park, Maryland 20742
301.405.5190 marcio@umd.edu

Name of Participant: ____

Participant's Age: ____

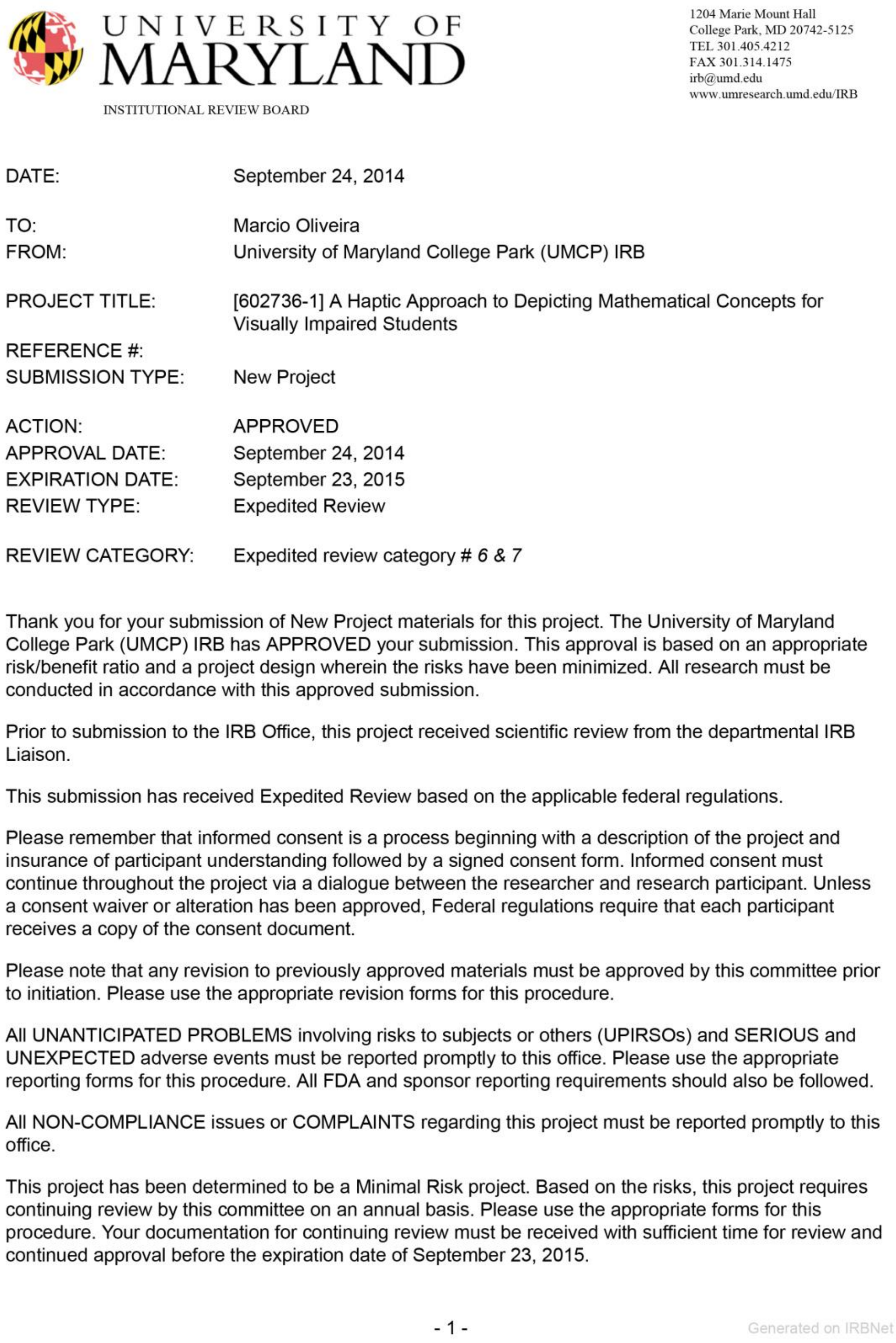
Printed name of Participant's Parent/Guardian:____________________________

Signature of Participant's Parent/Guardian:______________________________

Today's Date: ____

If you have questions about your rights as a research subject or wish to report a research-related injury, please contact: Institutional Review Board Office, University of Maryland, College Park, Maryland, 20742; (email) irb@umd.edu; (telephone) 301-405-0678

Appendix IV: IRB Approval Letter



UNIVERSITY OF MARYLAND
INSTITUTIONAL REVIEW BOARD

1204 Marie Mount Hall
College Park, MD 20742-5125
TEL 301.405.4212
FAX 301.314.1475
irb@umd.edu
www.umresearch.umd.edu/IRB

DATE: September 24, 2014

TO: Marcio Oliveira
FROM: University of Maryland College Park (UMCP) IRB

PROJECT TITLE: [602736-1] A Haptic Approach to Depicting Mathematical Concepts for Visually Impaired Students
REFERENCE #:
SUBMISSION TYPE: New Project

ACTION: APPROVED
APPROVAL DATE: September 24, 2014
EXPIRATION DATE: September 23, 2015
REVIEW TYPE: Expedited Review

REVIEW CATEGORY: Expedited review category # *6 & 7*

Thank you for your submission of New Project materials for this project. The University of Maryland College Park (UMCP) IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a project design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

Prior to submission to the IRB Office, this project received scientific review from the departmental IRB Liaison.

This submission has received Expedited Review based on the applicable federal regulations.

Please remember that informed consent is a process beginning with a description of the project and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the project via a dialogue between the researcher and research participant. Unless a consent waiver or alteration has been approved, Federal regulations require that each participant receives a copy of the consent document.

Please note that any revision to previously approved materials must be approved by this committee prior to initiation. Please use the appropriate revision forms for this procedure.

All UNANTICIPATED PROBLEMS involving risks to subjects or others (UPIRSOs) and SERIOUS and UNEXPECTED adverse events must be reported promptly to this office. Please use the appropriate reporting forms for this procedure. All FDA and sponsor reporting requirements should also be followed.

All NON-COMPLIANCE issues or COMPLAINTS regarding this project must be reported promptly to this office.

This project has been determined to be a Minimal Risk project. Based on the risks, this project requires continuing review by this committee on an annual basis. Please use the appropriate forms for this procedure. Your documentation for continuing review must be received with sufficient time for review and continued approval before the expiration date of September 23, 2015.

Please note that all research records must be retained for a minimum of seven years after the completion of the project.

If you have any questions, please contact the IRB Office at 301-405-4212 or irb@umd.edu. Please include your project title and reference number in all correspondence with this committee.